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W.Va. Geological & Economic Survey
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Petrology of the Upper Devonian Clastic Sequence in Lincoln and Jackson Counties, West Virginia and Wise County, Virginia

PRELIMINARY
OPEN-FILE REPORT
June 1980
SUBJECT TO REVISION

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ABSTRACT

Several hundred shale samples have been characterized with respect to mineralogic composition, chemical composition, and petrophysical properties. However, no compositionally based study reveals the fabric or manner in which the components are put together to form the resultant rock. Classification by fabric elements, based on X-radiography and thin section analysis, appears useful for interpretation of both depositional environments and reservoir properties of shale. Four lithic types based on fabric elements are defined in the Devonian shale of the study wells: 1) sharply-banded shale, 2) thinly-laminated shale, 3) lenticularly-laminated shale, 4) non -banded shale. Thinly-laminated and organic-rich lenticularly-laminated shales appear the most favorable types for gas productivity because the higher organic content of these lithic types probably acts as sites for significant sorption of gas which is slowly released during production.

Gas shows in five gas-shale wells located in western West Virginia and Virginia correlate with natural macroscopic fractures observed in core samples. Many natural fractures have no corresponding gas shows because of tight mineralization or closure at depth. High-angle and inclined fractures which remain open due to partial mineralization and propping caused by offsetting along fracture surfaces correlate with gas shows. Low-angle slickensided fractures do not increase rock permeability. Microscopic fractures in the rock matrix are rare and do not significantly contribute to permeability or porosity.

INTRODUCTION

The Devonian shale sequence is one of the oldest and least studied gas producing intervals in the Appalachian Basin. Production from individual wells generally occurs at modest rates. The average production of 955 active shale wells in nine West Virginia counties is 28 MCFPD (Bagnall and Ryan, 1976). However, production is of long duration, generally in excess of twenty years. The success ratio for Devonian shale gas wells in the 27 named fields in southwestern West Virginia is over 90% (Patchen, 1977) and high success ratios also exist in Kentucky, Ohio, and Pennsylvania. Although the Devonian shale sequence has not been a prime drilling target, recent natural gas shortages and price decontrols have generated considerable interest in the resource potential of the shale.

Shales have not been as intensely studied as other sedimentary rocks because of their fine grain size and lack of economic value. The Devonian shales of the Appalachian Basin are no exception. Thiessen (1925) and Hunter and Munyan (1932) described the Devonian shales in Eastern Kentucky and presented compositional data from transmitted light microscopy which indicates that regional mineralogic trends exist in the shale. Bates and Strahl (1957) investigated the occurrence of radioactive components within the shale and established a correlation between organic matter and uranium content. A limited description of sedimentary structures in the Devonian black shales of Tennessee is given in Conant and Swanson (1961). Utilizing two Devonian shale cores made available by the United States Department of Energy's Eastern Gas Shales Project, Larese and Heald (1977) made the first petrologic analysis of the Devonian shale from producing wells in West Virginia. They concluded that several shale lithologies are present in the vertical profile and that matrix properties of the shale and natural fractures may influence gas production.

With the availability of additional Devonian shale cores, this investigation was undertaken to define and characterize the compositional, diagenetic, and textural parameters of the Devonian shale interval and to relate these parameters to hydrocarbon accumulation and potential, geophysical log response, and depositional environment. Specific factors investigated include: detrital and authigenic mineral components, organic matter, bulk and matrix density, porosity, fabric elements, natural fractures and log response.

METHOD OF STUDY

Sample Source

Three oriented diamond drill cores located in Jackson and Lincoln counties, West Virginia and Wise county Virginia served as sample sources for this study (Fig. 1). The three wells had varying natural open flows: 1) Lincoln 1637 (Columbia Gas Transmission Co. 20403) - 198 mcfd, 2) Jackson 1369 (Columbia Gas Transmission Co. 11940) - 1007 mcfd, 3) Wise 253 (Columbia Gas Transmission Co. 20338) - 0 mcfd. Wells are indexed by the county permit number in this investigation. A total of 317 samples were chosen from approximately 1835 feet of core. Samples were selected as to be representative of specific lithologic units initially determined on the basis of rock color and relative silt content. In homogenous intervals, samples were chosen every 6 to 7 feet. Unusual sedimentary structures, lithologic contacts, and diagenetic features such as mineralized fractures were sampled to complement the representative samples.

Sample Preparation

Initially the core was cut NS perpendicular to bedding on a kerosene slab saw. One half was retained as an archive sample for analysis of sedimentary structures and fractures with such instruments as the stereoscopic scope. From the remaining half of the core, a 2 mm thick slab was cut for radiography and symmetrical subsections were cut for thin section, density, loss on ignition, x-ray and elemental analysis.

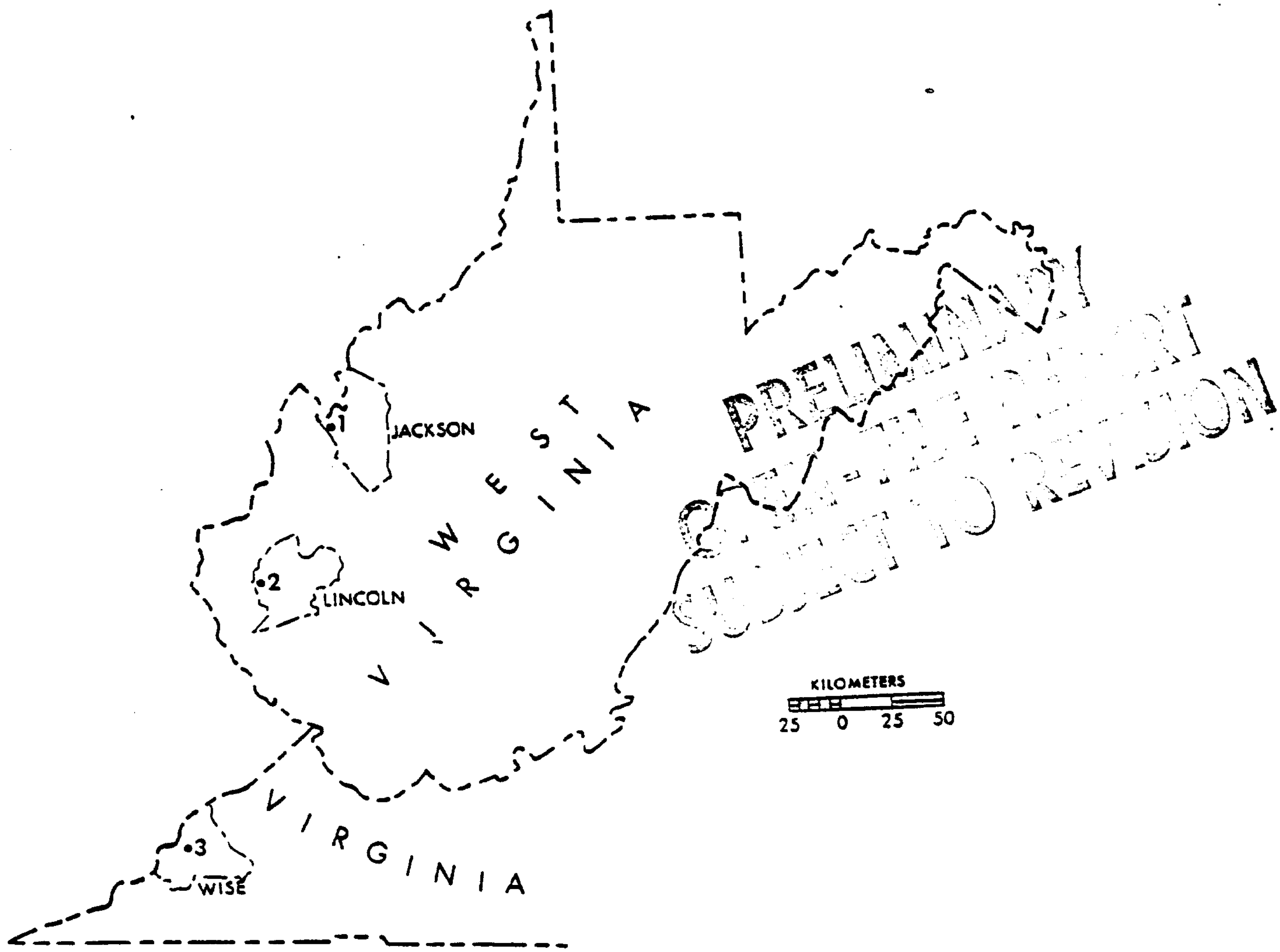

Figure 1. Location map of study wells: 1) Jackson 1369 (Columbia Gas Supply Co. #11940), 2) Lincoln 1637 (Columbia Gas Transmission Co. #20403), 3) Wise 253 (Columbia Gas Transmission Co. #20338).

Analytical Procedures

Radiography - The production of quality radiographs requires rock specimens prepared as thin uniform slabs to minimize image blurring. The brittle nature of many rocks causes slabs to crumble unless a backing of acetate is applied after thoroughly wetting the cut surface with acetone (R.E. Larese, 1977, pers. comm.) Thin acetate sheets are suited for use as a backing material as they cover the sample uniformly and are transparent to X-rays at the voltage utilized. A slab thickness of 2 mm was chosen as a standard thickness for this study. A Field Emission Corporation Faxatron 804 instrument with a 400-watt air-cooled tungsten tube was utilized. An X-ray source to specimen distance of 61 cm produced detailed radiographs. Kodak Type M film was used for its high resolution and short exposure time. A setting of 40 kV with a 2 minute exposure produced maximum specimen contrast. Positive prints were made on Kodak Rapid Polycontrast print paper.

Microscopy - Thin sections ground to a standard thickness of 30 microns were prepared for each sample. Mineralogic and organic components were counted in transmitted and reflected light at 500 X using an oil immersion objective for all samples from Lincoln 1637. Comparison of thin section derived compositional parameters with X-ray and loss on ignition data indicates that little predictive capability relative to mineralogic and organic components in Devonian shales can be gained from traditional point count techniques. A detailed description of the results is given in the characterization of Lincoln 1637. The remaining two wells were not point counted in detail. Silt content taken to be proportional to the amount of thin section quartz-feldspar is useful in making sedimentologic interpretations and was measured for all samples. The principal use of thin sections is in fabric analysis. Sedimentary structures including cross bedding, laminations, and burrows are abundant and show varied gross mineral distribution patterns which can be readily viewed in thin section.

Scanning electron microscopy (SEM) was employed to examine pore space, mineral morphology, and microfabric. Shale microfabric is easily disturbed by cutting or grinding and only freshly broken surfaces were examined. Shale chips approximately one centimeter square oriented parallel and perpendicular to bedding were examined. Mineral identification was made using the accompanying x-ray energy dispersive microanalyzer. Organic matter was separated from the rock matrix by dissolution in hydrofluoric and hydrochloric acid followed by gravity separation in bromoform prior to SEM examination.

Density-Porosity - Four types of density were derived for each sample from the subject wells: bulk density, matrix density, material balance density, and log density.

Bulk density was measured by weighing krylon coated blocks of shale (about 30 gms) in air and kerosene. Bulk density can be calculated as: (weight in air)/(weight loss) x (density of immersion fluid). Precision of bulk density is approximately 0.01 g/cc.

Matrix density was calculated using the method of Nuhfer (1979). After being ground in a Spex Mixer-Mill, the powdered shale was placed in a metal crucible and weighed in air on an electric balance. The sample was then placed in a vacuum chamber and evacuated to about 0.2 mm of mercury. Kerosene was slowly added to the crucible until it covered the powder. The sample remained under vacuum until outgassing from the shale ceased which was assumed to indicate that the pores were saturated with kerosene. The crucible was placed on a metal pan connected to the bottom of the balance and immersed in an underlying pan of kerosene and reweighed. Matrix density can be calculated as: (weight in air)/(weight loss) x (density of immersion fluid). Precision of matrix density is approximately 0.01 g/cc.

Material balance density was computed from the whole rock composition as established by estimates of organic matter from loss on ignition between 100 and 550°C, from non-pyritic mineralogy as determined by x-ray diffraction and pyritic mineralogy as back calculated from total sulfur content. Material balance density was used as a check against matrix density to locate samples with a large disparity in density values. Pyrite nodules embedded in the density black or ground in the rock powder were the major cause of discrepancy between the two density values.

Log density was taken from the bulk density log at the log depth subjectively selected as corresponding to the sample depth taken from the core. Core depth could be corrected to log depth only for the Lincoln 1637 core.

Matrix porosity was calculated from bulk and matrix density as: %Ø = (matrix density) - (bulk density)/(matrix density) x 100 where the density of pore filling fluids is assumed to be zero. Precision of porosity measurements is approximately ±0.5%.

<u>Loss on Ignition</u> - Organic matter in Devonian shale was measured by LOI between 100 and 550°C. A sample of ground shale (2 mg minimum) was dried at 100°C to remove moisture. After weighing, the sample was heated in a muffle furnace for four hours at 550°C. The subsequent weight loss was assumed to represent loss of organic matter. X-ray analysis indicated less that one percent kaolinite and swelling clays which would lose water at 550°C and contribute to the weight loss. Dean (1974) found a high correlation between organic carbon determined by a C-H-N analyzer and organic content measured by ignition for recent alke sediments with the mean ignition loss approximately equal to twice the organic carbon content.

A second loss on ingition between 550 and 1000°C reflected loss of CO_2 from carbonates, some S from sulfides, and tightly bound water in clay minerals. Precision is about ±5% per determination for the two ignitions with variations being caused by sample inhomogeneity and non-uniform heating in the muffle furnace.

<u>X-ray and Elemental Analysis</u> - A semi-quantitative estimation of shale mineral content was made using weighted x-ray diffraction data as detailed in Renton (1979). Weighting factors for the x-ray diffraction data are calculated

from samples on which both diffraction analyses and elemental analyses are available. Initial estimates of mineral concentration are made by dividing the intensity of the strongest uninterfered peak for a mineral by the sum total of the strong peaks for all mineral phases present. Using standard formulas for the minerals present, elemental concentrations can be calculated from the x-ray diffraction mineral percentages. From the elemental concentrations determined for Devonian shales by x-ray floresence, mineral concentrations are calculated. The two sets of elemental data are compared, and the calculated mineral concentrations are adjusted until the calculated elemental analysis closely fits the measured elemental analysis. Weighting factors are calculated by dividing the x-ray intensity values into the calculated mineral concentrations. For the Devonian shales, a good correlation of the measured elemental concentration with the calculated elemental concentration occurs for Si, Al, Fe, and K indicating that the calculated mineral concentrations are good estimates of the true mineral concentrations for the major mineral components present (Renton, 1979). No other method for mineralogic analysis of shales exists to evaluate the accuracy of this method.

GEOLOGIC SETTING

Structural Setting

The three study wells had varied structural settings (Figure 2). Jackson 1369 is located near the southwest boundary of the Devonian shale Cottageville gas field. This well overlies a NE-SW trend of sedimentary rocks draped over a basement fault as interpreted by Sundheimer from seismic data. Structure contour maps by Nuchols (1978) on the tops of the Berea Sandstone and productive lower portion of the Huron Member did not show any faults in these units within a mile of Jackson 1369. The Rome Trough (Basement structure) is parallel to the NE-SW trend of high producing Devonian shale gas wells in the Cottageville Field and is taken to be a major cause of fracture permeability in the shale. Harris (1978) states that the trough was active through the Silurian and that small recurrent movement along flanking faults may have fractured late Paleozoic strata.

Lincoln 1637 lies over the Rome Trough. The well is located in a syncline being bounded to the northwest by unnamed anticlines and to the southeast by the Warfield Anticline. Columbia Gas reports that this well was located near the intersection of short lineaments as revealed by high altitude photographs.

Wise 253 is located on the Pine Mountain Thrust Plate. The well intersects the Pine Mountain Falut in the Devonian shale section. Columbia Gas reports the presence of photolineaments as a factor in well site location.

Stratigraphic Setting

The Devonian shale sequence in West Virginia and Virginia is defined as

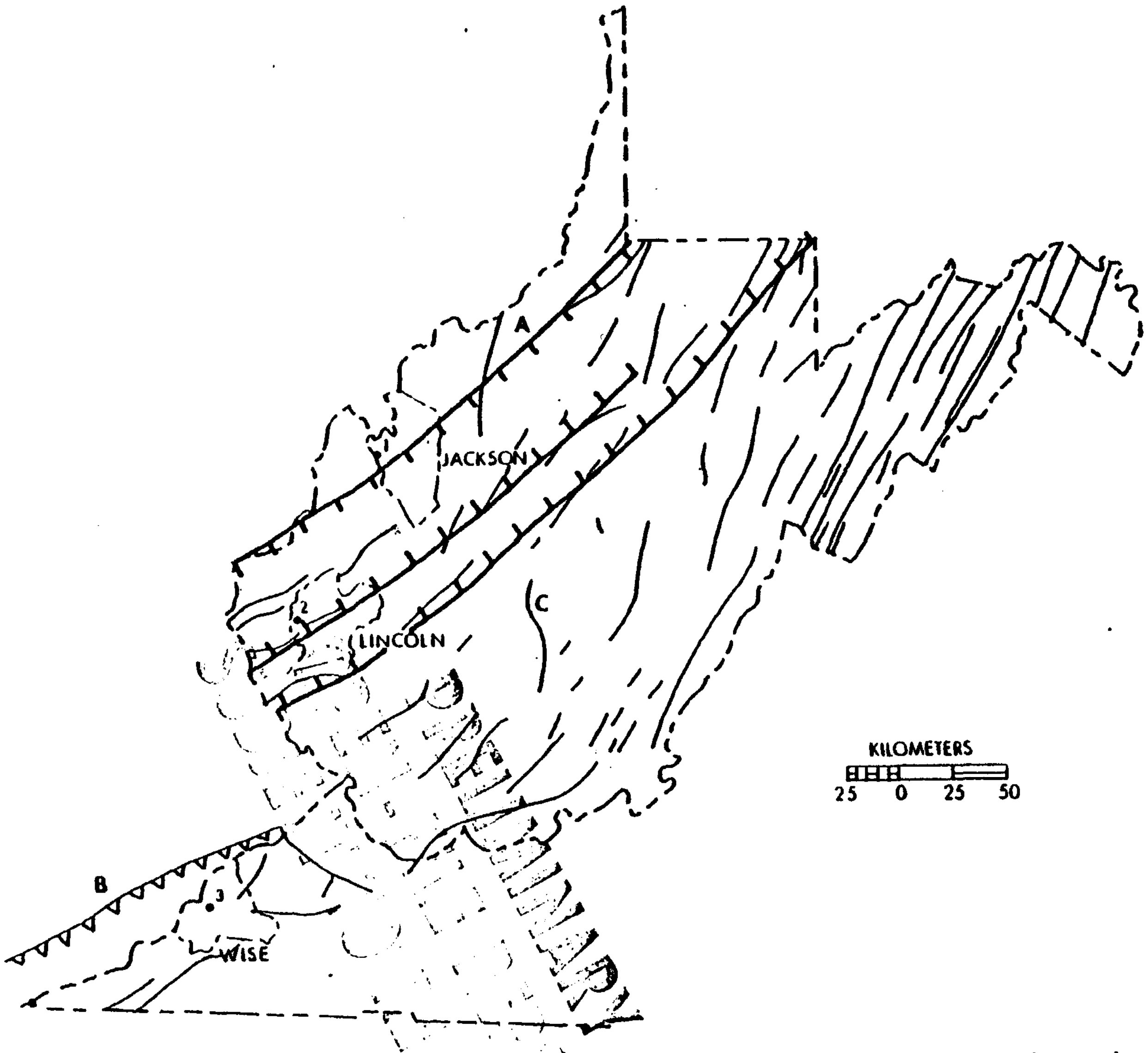

Figure 2. Structural setting of study wells. Wells are indexed to county permit numbers: 1) Jackson 1369, 2)Lincoln 1637, 3) Wise 253, Structural elements are: A) Rome Trough, B) Pine Mountain Thrust, C) Anticlinal axes.

the interval between the top of the Onondaga Limestone and its equivalents to the base of the Berea Sandstone or its equivalents (Fig. 3). The study wells do not sample the complete shale section. The Middle and lower portion of the Upper Devonian shales, Marcellus Formation through Sonyea Formation, is absent in western West Virginia because of erosion. A regional unconformity which progressively overlies older stratigraphic units to the west extends from the subsurface in eastern West Virginia to the Devonian outcrops in Ohio (Schwietering, 1979).

From bottom to top, the Devonian shale section present in western West Virginia consists of the Rhinestreet and Angola Shale Members of the West Falls Group, the Java Formation, and the Ohio Shale Formations as defined on gamma ray logs by Neal (1979). The Huron Member in western West Virginia is broken up into three informal units (Figure 4). The lower portion of the Huron is a radioactive black shale extending from the top of the Java to the base of a thick, gray shale tongue (middle portion of Huron) which is recognized on gamma ray logs by its lower radioactivity. The top of the middle portion of the Huron is defined by the basal radioactive black shales of the upper portion of the Huron.

The black shales of the Rhinestreet Member and lower portion of the Huron Member are the principal gas producing units in the shale section. In extreme western West Virginia, the black Cleveland Shale Member of the Ohio Shale is present. Provo (1977) defines the Three Lick Bed as an intertonguing sequence of grey and black shale that is equivalent to portions of the Chagrin Member of the Ohio Shale. The Three Lick Bed is only recognizable in extreme western West Virginia, in eastern Kentucky, and in south-central Ohio.

Traced eastwards, the shale formations experience facies changes reflecting the influx of coarser clastics from the prograding Catskill deltaic complex (Schwietering, 1979) (Fig. 4). The Rhinestreet black shales pinch out and the gray-green shales of the Angola Shale Member and Java Formation grade into the silty shales, siltstones, and fine sandstones of the Braller Formation. Sim-

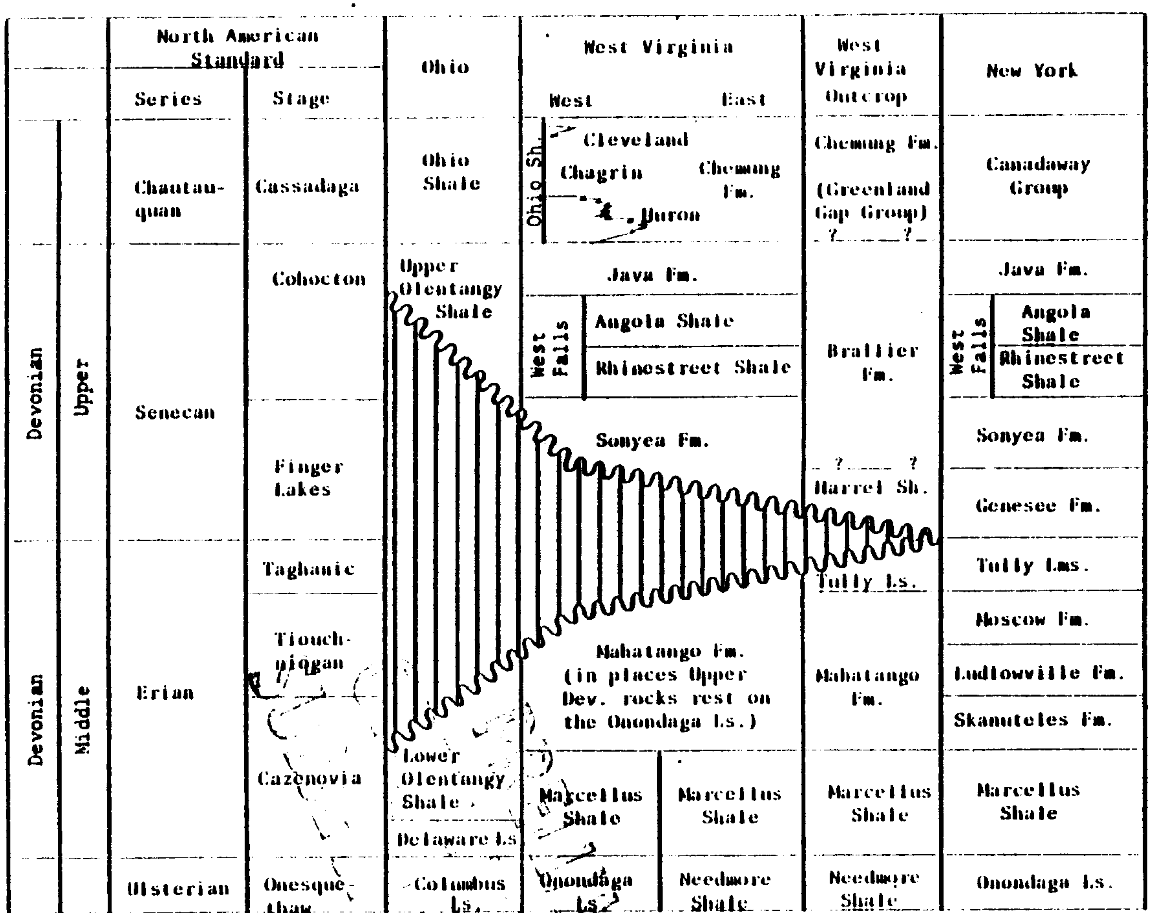

Figure 3. Current stratigraphic terminology of Middle and Upper Devonian strata in New York, Ohio, and West Virginia. Personal communication. Joe Schwietering (1979).

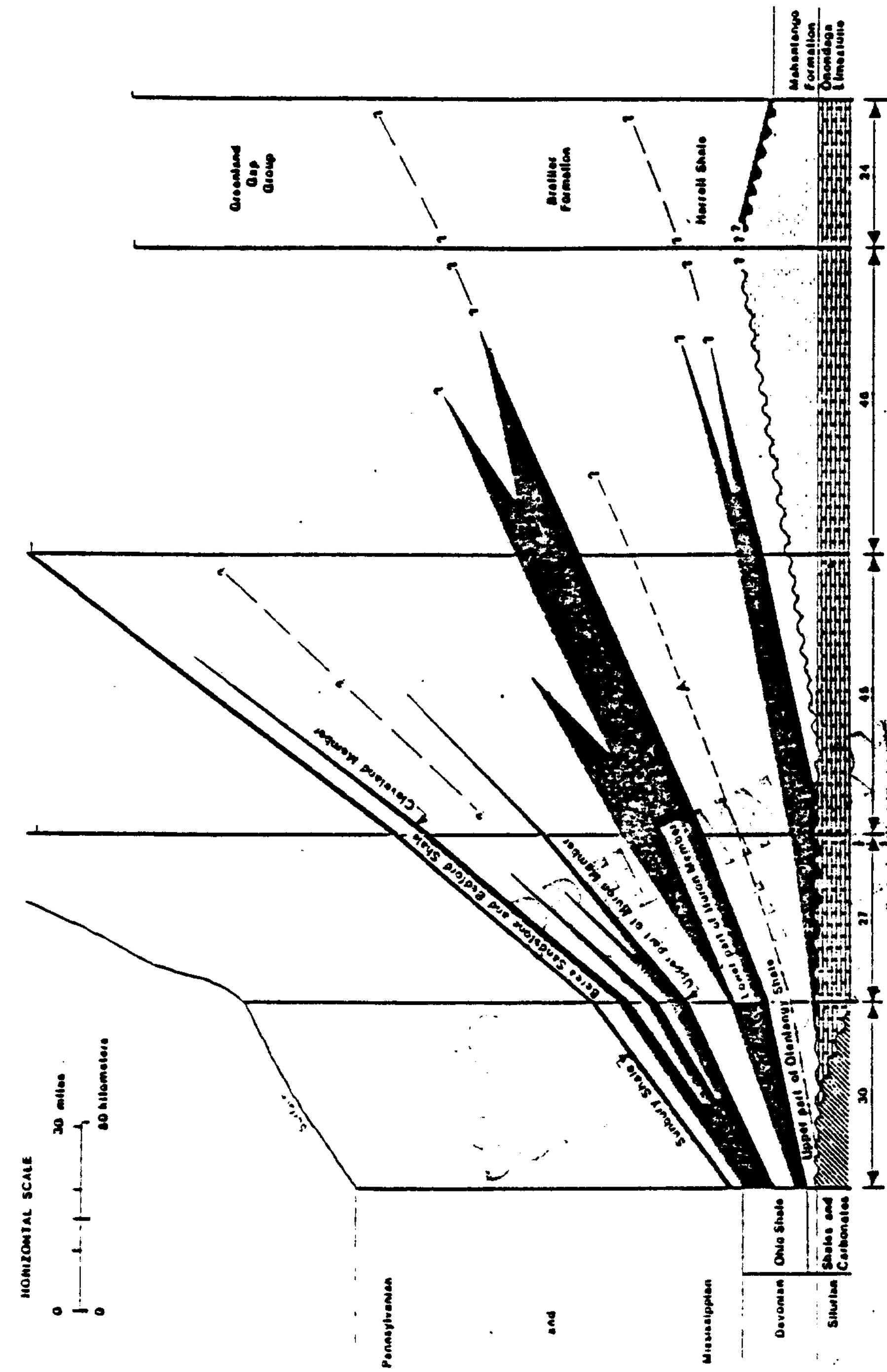

Figure 4. Stratigraphic relationships of Devonian-Mississippian black shales from eastern Kentucky across southern West Virginia. From Schwietering (1979).

ilarly, the black shales of Huron Member and Cleveland Shale Member pinch out and pass into the coarser clastics of the Greenland Gap Group (Chemung) and Catskill Group.

Lincoln 1637 is the only complete core of the entire Upper Devonian shale section present in western West Virginia. The section consists (bottom to top) of the Rhinestreet and Angola Shale Members of the West Falls Group, Java Formation, Huron Member of the Ohio Shale, and undifferentiated shales of the Ohio Shale between the Huron Member and Berea Sandstone. The Rhinestreet Shale Member rests unconformably on the Onondaga Limestone.

The Jackson 1369 partial core recovered only the lower portion of the Huron Member which consists of two black shale tongues separated by an interval of grey shale.

The Wise 253 core contains sections of the lower, middle and upper portions of the Huron Member, Three Lick Bed, and Cleveland Member. The lower portion of the Huron Member is the only shale unit represented in all study cores.

CLASSIFICATION OF LITHOLOGIC TYPES

Classifications For Fine-Grained Sedimentary Rocks

As is the case with sandstones and limestones, many classifications have also been proposed for fine-grained sedimentary rocks (Table 1). Parameters used in classification include texture (particle size), fissibility (structure), mineral composition, chemical composition, color, tectonic-environmental setting, and degree of metamorphism.

Texture-Fissility - Texture and fissility appear to be the two parameters used in commonly accepted classification schemes for fine-grained sedimentary rocks (Folk, 1961, 1968; Dunbar and Rodgers, 1957; Picard, 1971). In Folk's classification, sediments composed of silt and clay-size grains, with nether fraction comprising more than two-thirds of the total, are termed mud. Silt has over two-thirds silt-size grains and clay has over two-thirds clay-size grains. On induration, massive varieties are termed mudstone, siltstone, and claystone. Fissle counterparts are mud shale, silt shale, and clay shale.

Picard (1971) used particle size as the most significant property in classifying fine-grained sedimentary rocks. Using the proportions of clay, silt and sand, he defined four major groups: claystone, siltstone, mudstone and sandstone. Claystone, siltstone and sandstone contain more than 50 percent clay, silt, or sand-sized grains, respectively. Mudstone contains less than 50 percent of clay, silt, or sand. Silty and sandy are modifiers of claystone, when clay-sized grains are less than 75 percent but more than 50 percent. Primary adjectives are based on the dominant clay mineral present. Fissility does not form a primary part of this classification and is used only as a descriptive adjective.

Mineralogic-Chemical Composition - The availability of automated x-ray diffraction and fluoresence units make compositional determinations on large numbers of samples relatively easy to acquire. The comparison of x-ray diffraction data

Source	Texture - Particle Size	Fissibility - Structure	Tectonic Setting	Mineral Composition	Color	Chemical Composition	Degree of Metamorphism
Wentworth (1922)	X						
Twenhofel (1937)	X						X
Alling (1945)		X					
Krumbein (1947)			X				
Shrock (1948)	X						
Pettijohn (1949)			X				
Twenhofel (1950)	X	X	X		X		
Trefethen (1950)	X						
Dapples and others (1950)	X		X	X	X		
Krumbein and Sloss (1951)	X		X	X		X	
Flawn (1953)	X	X					X
Ingram (1953)	X	X					
Shepard (1954)	X						
Pettijohn (1957)			X		X	X	
Dunbar and Rodgers (1957)	X	X					
Gorsline (1960)	X						
Krumbein and Sloss (1963)	X						
Folk (1961, 1968)	X	X					
Picard (1966, 1971)	X			X			
Lewan (1978)	X			X		X	
Nuhfer and Vinopal (1979)		X					

Table 1. Criteria used for classification of fine-grained clastic rocks and sediments. Adapted from Picard (1971).

with corresponding elemental analysis improves the accuracy of quantitative x-ray diffraction data (Renton, 1979). For fine-grained sedimentary rocks, this approach is the best method for constructing mineralogic or elemental based classifications.

Lewan (1978) proposed a classification based on mineralogy and grain size. Shale contains more than 65% by volume microscopic material (<5 um), and mudstone contains 65% to 45% microscopic material by volume. Fissility is not used as a criteria in distinguishing shale from mudstone. Shales are further subdivided by the weight percentage fraction of silicates in the rocks into the following groups: claystone (silicate fraction = 100% to 75% by weight), marlstone (silicate fraction = 75% to 25% by weight), and micstone (silicate fraction is less than 25% by weight). Primary adjectives are derived from the mineral or group of minerals that exceed 50% by weight. Nominal adjectives include color, splitting, bedding, organic richness, and fossil content.

Color - On viewing a thick section of mudrock in outcrops or cores, the most readily noticeable difference in the vertical profile is color. The color of a mudrock, although controlled by chemical and mineralogic compositon, is not defined by a unique combination of mineral and chemical constituents. Red and purple shales contain more hematite than green shales. With increasing hydration of ferric oxides, yellows and browns are produced (Blatt et. al., 1972). Green mudrocks result from the presence of green phyllosilicates (illite, chlorite, and glauconite) and the absence of other pigmenting agents such as hematite and organic matter. Organic matter causes darkening of mudrocks from grey to black. A study of the relationship between color and organic carbon content in sediments by Frask and Patnode (1937) has shown a wide scatter of carbon contents for a given tone. This effect was attributed to: different types of organic matter, the presence of finely dispersed iron sulfides, and the effect of other pigmenting agents which may mask the organic matter. Color does not in many cases provide any significant information on the composition or texture of a mudrock and thus, should not be the basis of a classification.

Environmental Setting - Krumbein (1947) proposed a general tectonic and environmental classification of shales. Parameters used in classification are: thickness of the shale body, widespread or local occurrence of shale, lateral thickness changes, lithologic uniformity, and associated rock types. Krumbein recognized four tectonic-environmental associations on the basis of the above properties: widespread stable platform with no strong positive areas, fairly stable platform associated with unstable source areas, relatively shallow intracratonic basins with mildly positive or relatively remote source areas, and tectonically active marginal geosynclines with strong positive source areas. Dapples and others (1950) built on Krumbeins classification and assigned tectonic settings to shales based on their mineralogy. The shale classes were: quartzose shale (stable shelf), quartzose-subgraywacke-arkosic shale (unstable shelf) and graywacke shale (geosynclinal). These attempts to construct a genetic classification that reflects the origin of a particular shale type have not been successful as similar mudrocks can be produced in similar sedimentary environments.

Classification Approach Used in This Study

Based on the foregoing brief review of classifications for fine-grained sedimentary rocks, it was concluded that texture, structure, and mineralogy are the properties most applicable for classifying fine-grained sedimentary rocks. The concept of classification is not essential to a study. Data can be presented graphically to show lateral or vertical changes in the rock body and relationships between variable can be analyzed by various statistical techniques. However, given the number of samples available and the amount of compositional and petrophysical data gathered, an attempt was made to find natural boundaries in this little studied rock body. If antural rock boundaries based on composition and/or texture exist in the Devonian shales, the classes so defined would be useful in characterizing stratigraphic units and perhaps in interpreting depositional environments. The 196 samples from Lincoln 1637 which span the entire Devonian shale section present in western West Virginia were initially analyzed.

Texture, Particle Size - The silt percentage of a sample was determined by point counting under a petrographic microscope with transmitted light. Quartz, chert, and feldspar grains were counted as silt. The volume fraction of silt grains thus derived appears to become unreliable when many of the grains are less than 30 microns in size because of overlapping by clays. Comparison of thin section silt with elemental silicon in the 1300 foot vertical profile of Lincoln 1637 seems to bear out this concern (Fig. 5). The silt curve shows a significant increase up section while the silicon curve shows only a slight increase which is not great enough to account for the large apparent increase in silt. Total quartz content as measured by x-ray diffraction shows only a slight increase up section and is in close agreement with the silicon trend. Larese and Heald (1977) showed a trend of increasing silt size uphole in Lincoln 1637. The increase in silt seen in thin section uphole is interpreted as reflecting increased visual detection of silt because of its increasing grain size.

Blatt and Schultz (1976) determined that the crystalline silica fraction of the average mudrock is one-eight sand size, six-eights silt size, and one-eight clay size. Assigning one eighth of the x-ray determined quartz to the clay size fraction still does not resolve the large discrepancy between thin section quartz-feldspar (silt) and x-ray quartz-feldspar in Lincoln 1637. It is concluded that the x-ray derived quartz-feldspar percentage multiplied by a factor of seven-eights probably represents the best measure of silt content in the Devonian shales. Silt content is of limited value in distinguishing stratigraphic units or marking

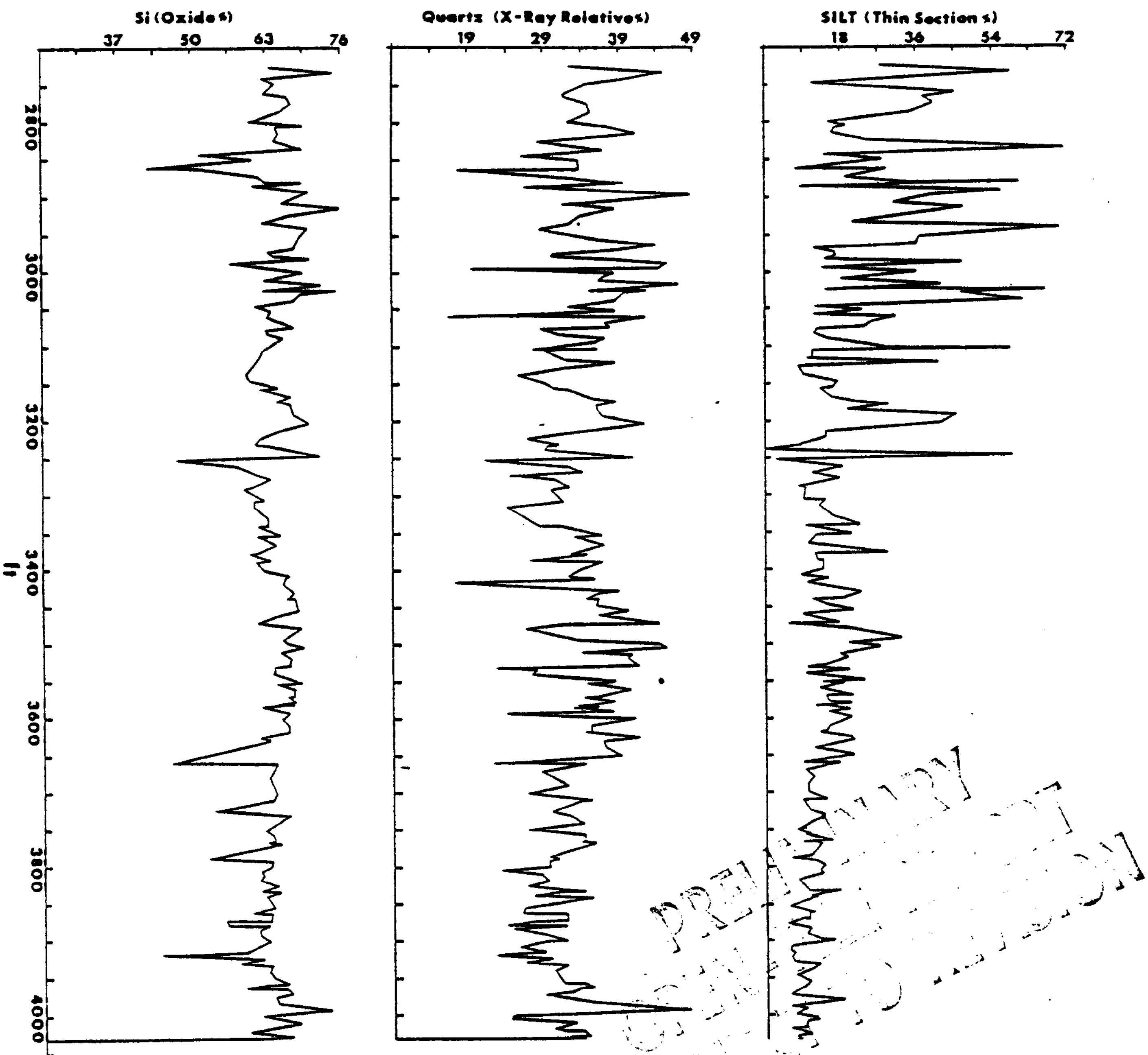

Figure 5. Strip logs of Si oxide measured by X-ray fluoresence, quartz measured by X-ray diffraction and silt measured in thin section for Lincoln 1637. The trends of the elemental Si and and X-ray quartz profiles are in close agreement and indicate little change in the vertical profile. Their discrepancy with the trend of the silt curve suggests that a large part of the quartz fraction is not visible in thin section in the lower part of the well. The Si oxide curve has 40 less data points.

natural lithologic boundaries in the 1308 foot vertical profile of Lincoln 1637, except for defining a small number of argillaceous siltstones.

Composition and physical properties - Mineral percentages derived from x-ray diffraction data, thin section silt, loss on ignition (100-550°C, 550-1000°C), porosity, bulk-matrix density, and geophysical log responses were used to determine if any natural compositional or physical boundaries exist in the vertical sample profile. Factor analysis was run on standardized data. This multivariate technique has been useful in separating sediments deposited in different sedimentary environments (Davis, 1973) and in determining relationships between petrographic variables (Smith, 1969). The relative importance of individual variables that characterize a factor is reflected in the magnitude of the variable loadings for a specific factor (Fig. 6).

The first factor is dominated by quartz, thin section silty (which is likely proportional to changes in silt size), and illite. Illite and quartz-silt show inverse loadings. Illite and quartz are by far the two dominant minerals in the samples and a relative increase in one produces a decrease in the other since the mineral data sum to 100 percent. Thus, this factor is basically the silt/clay ratio. The second factor is dominated by organic matter (LOI 100-550°C), pyrite, sulfur, resistivity log, sonic log, and gamma ray log values. The distinctive log readings are all related to organic matter. A positive correlation between organic carbon content and uranium in the Devonian shale sequence in West Virginia was established by Leventhal (1977). It has long been known that higher organic matter content correlates with higher resistivity and interval transit time. Pyrite is associated with organic matter as both are stable in a reducing environment. Bulk and matrix density show strong negative loading because they are negatively correlated with organic content.

A plot of the first and second factors was subjectively separated into three groups. quartz "rich" shale, clay "rich" shale and organic "rich" shale (Fig. 7). Although some separation seems to be possible on the basis of the silt/clay ratio

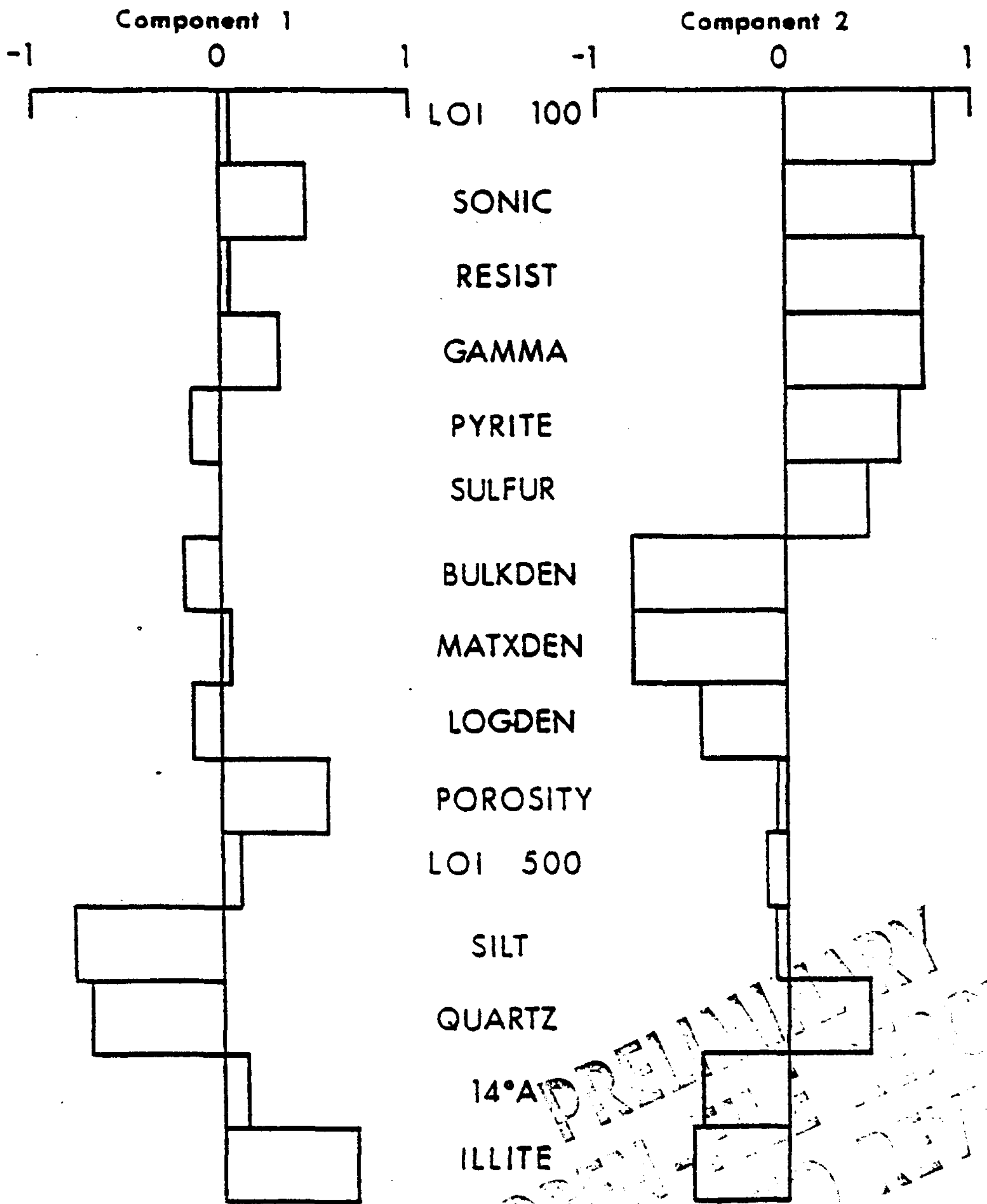

Figure 6. Loadings of variables on the first two principal components of Lincoln 1637 data. The first principal componnent represents the quartz/clay ratio. The second principal component is dominated by organic matter (LOI 100), pyrite sulfur, and geophysical log responses produced by organic matter.

(factor 1), tabulation of the mean quartz content for the clay "rich" and quartz "rich" groupings shows that there is approximately a 4 percent difference between the two groups. This small difference is not taken to represent a geologically significant difference between the two groups. It is concluded that the major compositional variable useful in classifying Devonian shales is organic matter. Organic matter, through its associated elements or by its physical properties produces the log responses that are used to distinguish stratigraphic units in the Devonian shales of western West Virginia.

Fabric - The presence or absence of fissility has commonly been used as a criteria to classify shale and mudstone respectively. Fisility is controlled by rock fabric (Byers, 1974). A vertical profile of x-radiograph positive prints from Lincoln 1637 indicated that fabric elements revealed more contrast between samples than any mineralogical variable. In addition, the formal stratigraphic units defined by geophysical logs were generally dominated by mudrocks which possess similar sedimentary structures. Laminations and bioturbation features were the primary sedimentary structures that differentiated samples. Four repetitive associations of these sedimentary structures were observed in the core defining four classes or lithologic types: thinly-laminated shale, lenticularly-laminated shale, non-banded shale, and sharply-banded shale. The word shale is used throughout this paper as a fine grained sedimentary rock containing less than 50% silt and sand sized grians. This classification was found to be applicable to the other wells studied. As with any rock classification, gradations exist and class boundaries are not perfectly delineated. The following descriptions and illustrations show the representative variation present within each class.

Thinly-laminated shale - Thinly-laminated shale is characterized by laminae generally less than 2 mm in thickness. A lamiantion is defined as the smallest megascopic layer visible in the radiograph (Campbell, 1967). The light and dark

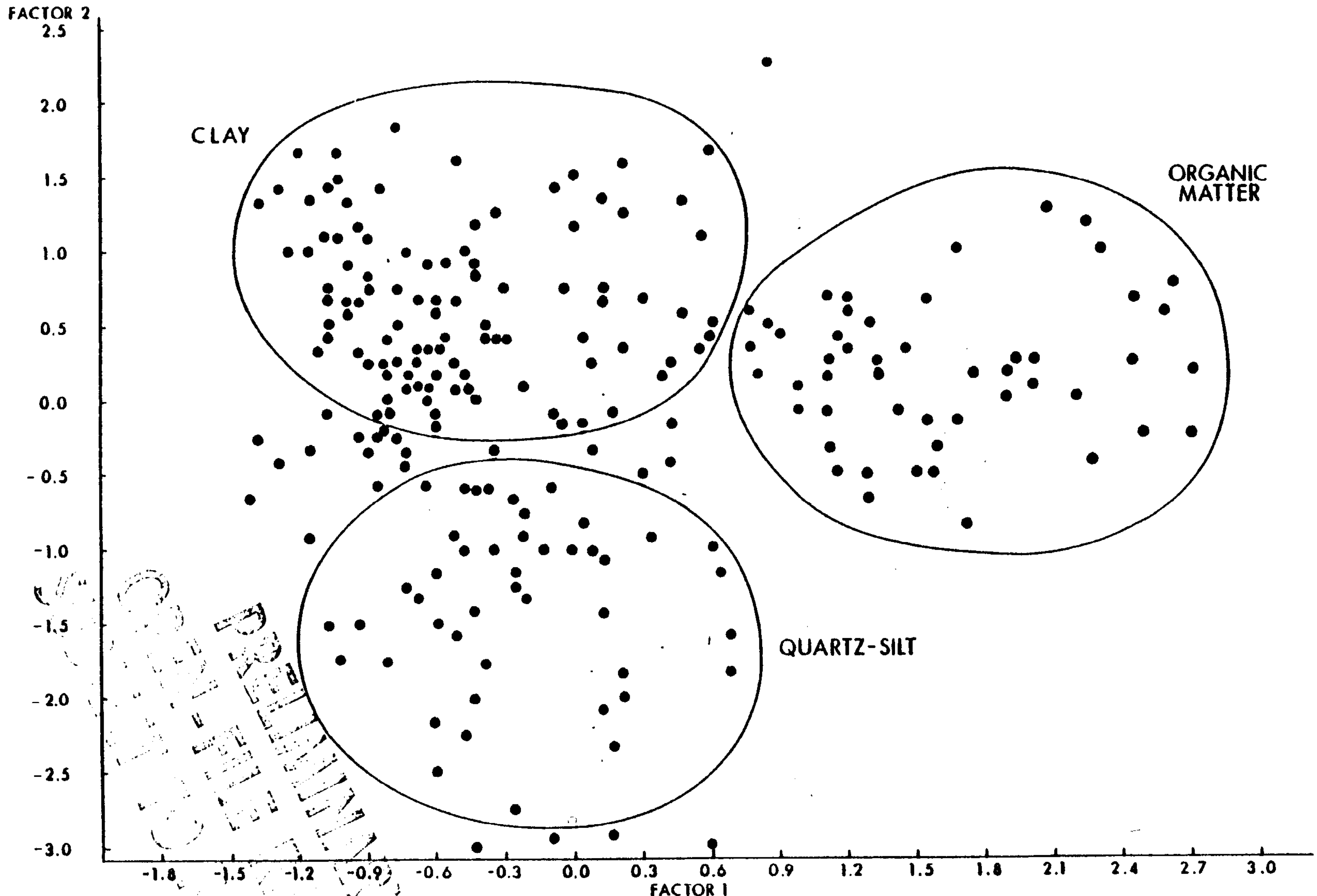

Figure 7. Mineralogical and petrophysical variables from Lincoln 1637 samples plotted against the first two principal components. Three groupings are recognized: clay "rich" shale, quartz "rich" shale, and organic "rich shale.

layering which define the lamina are caused by varying concentrations of silt, clay, organic matter, and pyritic matter in the layers. Contacts between lamina are sharp. More than two thirds of the laminae extend the width of the slab, but some are discontinuous. Bioturbation features are uncommon and generally consist of horizontal burrows or trails which disrupt a few lamina. Silt occurs as dispersed grain, but more commonly is concentrated into lenses a few grains thick. Pyritic material is generally silt sized or smaller and is concentrated into laminae which have dark tones on the radiograph print. Representative illustrations are given in figure 8.

Lenticularly-laminated shale - In lenticularly laminated shales, there are fewer laminae per vertical unit. The laminae are more discontinuous with fewer than two-thirds extending the width of the core and contacts between laminae are less distinct than in thinly laminated shale. Radiographs have a resultant streaked appearance (Figure 9). Horizontal and subvertical burrows are common. The light to dark laminae result from varying concentrations of silt, pyrite, and organic matter. Pyrite also commonly occurs as nodular burrow fillings and wiry forms which might be synaresis cracks or gas vesicle fillings.

Nonbanded shale - Non-banded shales have virtually no laminae or bands that extend the full width of the slab. This shale type is equivalent to Folk's (1964) mudstone or claystone. Bioturbation mottling is the dominant sedimentary structure and in some samples, vestiges of laminae or bands are visible suggesting that organisms destroyed pre-existing linear structures in the sediment. Pyritic matter and silt are disseminated through the rock. Representative illustrations are shown in figure 10.

Sharply-banded shale - Repetitive interbedding of laminated and nonbanded shale define the sharply banded shale type (Fig. 11). Bands are greater than a centimeter in thickness and are thin beds in the sense of representing a sedimentation unit deposited under essentially constant physical conditions

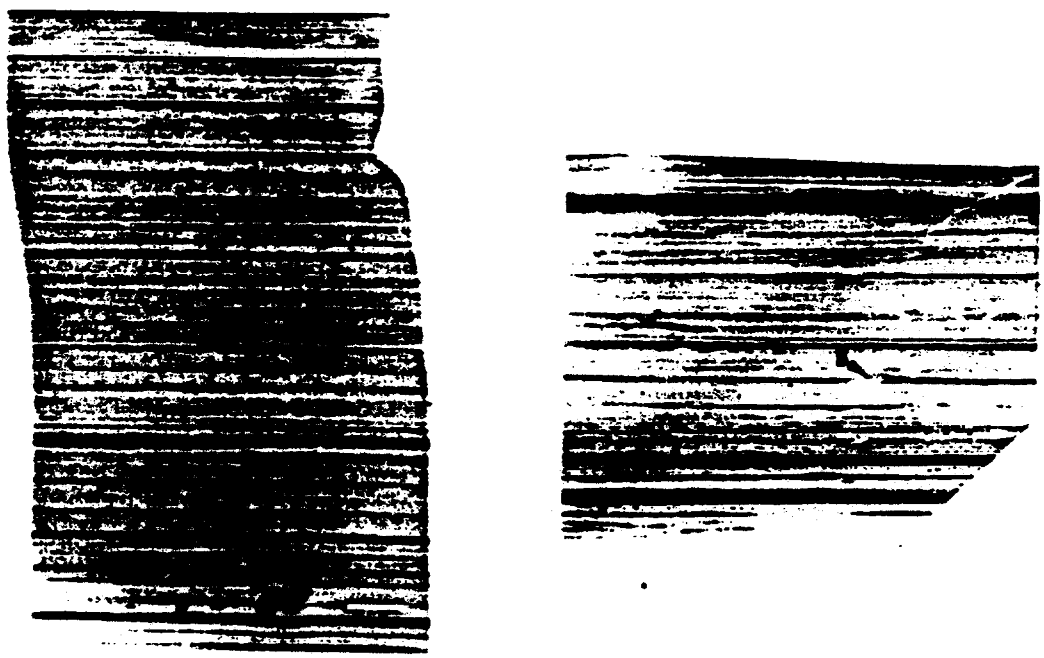

Figure 8. Radiographs. A) thinly-laminated shale in the Rhinestreet Member of the West Falls Formation. Differences in the amounts of clay, quartz, organic matter, and pyrite produce the radiographic tonal differences. Pyrite rich laminae possess the darkest tones. Virtually all laminae are continuous across the slab with sharp contacts. Burrows or trails suggestive of benthonic invertebrates are absent. Laminae show compaction around pyrite nodule (P). From Lincoln 1637 at core depth 4027. B) Thinly-laminated shale in the Three Lick Bed of the Ohio Shale. Laminae are dominant feature, but many do not extend across the slab. Laminae boundaries are becoming diffuse and undulatory. Horizontal burrows are recognizable (B) and along with feeding or movement trails may have been a factor in disrupting laminae. Sand size pyrite (dark bodies) is becoming dispersed through the rock or concentrated into broad bands. From Wise 253 at core depth 4903.4. Scale bar is one centimeter. (Sharp white streaks are cracks in the samples).

Figure 9. Radiographs. A) Lenticularly laminated shale in the Rhinestreet Member of the West Falls Formation. Laminae are less continuous than in thinly laminated shale with fewer than two thirds of the laminae extending across the slab. The laminae show diffuse boundaries and undulatory contacts (B). Disruption of laminae by burrowing as at (D) is not uncommon. From Lincoln 1637 at core depth 3838.5. B) Lenticularly laminated shale in the lower portion of the Huron Member of the Ohio Shale. Virtually all laminae are discontinuous with diffuse boundaries giving the sample a streaky appearance (L). Well defined burrows are not common. From Jackson 1369 at core depth 3795. Scale bar is one centimeter.

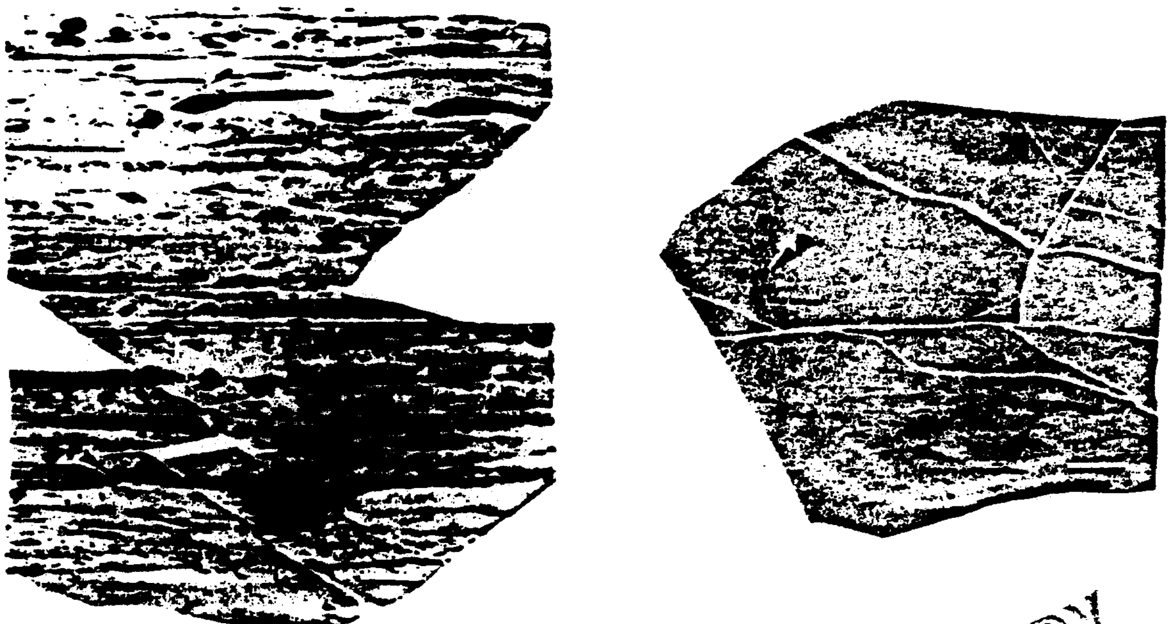

Figure 10. Radiographs. A) Nonbanded shale in the Rhinestreet Member of the West Falls Formation. Few laminae or bands extend across the slab. This sample shows extensive pyritization of burrow fillings. Vestiges of pyrite rich laminae or bands are visible (P) and may be concentrations of fecal pellets that were later compacted and pyritized. From Lincoln 1637 at core depth 3883. B) Nonbanded shale in the Java Formation. Macroscopic linear fabric elements are lacking. Some small burrows or perhaps gas vesicles are filled with pyrite (P). Burrowing organisms have completely homogenized the sediment destroying the original fabric. Evidence of burrowing is seen in this section. From Lincoln 1637 at core depth 3740. Scale bar is one centimeter.

Figure 11. Radiographs. A) Sharply-banded shale in the undifferentiated shale above the Huron Member. The linear fabric is defined by wide bands of alternating light and dark shale. Pyrite-organic rich bands are darker on the prints and typically contain laminae. Lighter bands contain less pyrite-organic matter and commonly show burrow mottling (B). Pyritized spores or algae (P) are commonly concentrated at the base of the lighter bands. From Lincoln 1637 at core depth 2899. B) Sharply-banded shale in the lower portion of the Huron Member. A siltstone (S) is interbedded with bands of gray shale. Pyritized spores and algae are concentrated along the scour surface at the base of the siltstone band. Dark band near bottom contains large spheroidal pyrite particles at base and finer disseminated pyrite throughout. Laminae are present above the heavily pyritized band. From Jackson 1369 at core depth 3641. Scale bar is one centimeter.

(Otto, 1938). Contacts between bands are generally sharp and the bands may show internal structures such as laminae or burrows. Thin siltstone beds are commonly associated with the shale.

Compositional Parameters and Rock Fabric

The previously discussed textural classification of shales was devised independently of any compositional or petrophysical variable. Plotting the four fabric types from the Lincoln 1637 samples on the factor analysis plot of compositional data (Fig. 7) indicates that rock fabric reflects some compositional trends (Fig. 12). Most thinly-laminated and nonbanded shales fall within the clay "rich" grouping, and sharply banded shales fall within the quartz "rich" grouping. Thus, approximations of compositional and physical parameters can be made to a limited extent by knowing the rock fabric. On the basis of the general agreement between the compositional and textural properties it was decided that classification of samples into lithologic types on the basis of rock fabric would be useful in characterizing stratigraphic units and might aid in explaining their depositional environment and reservoir properties.

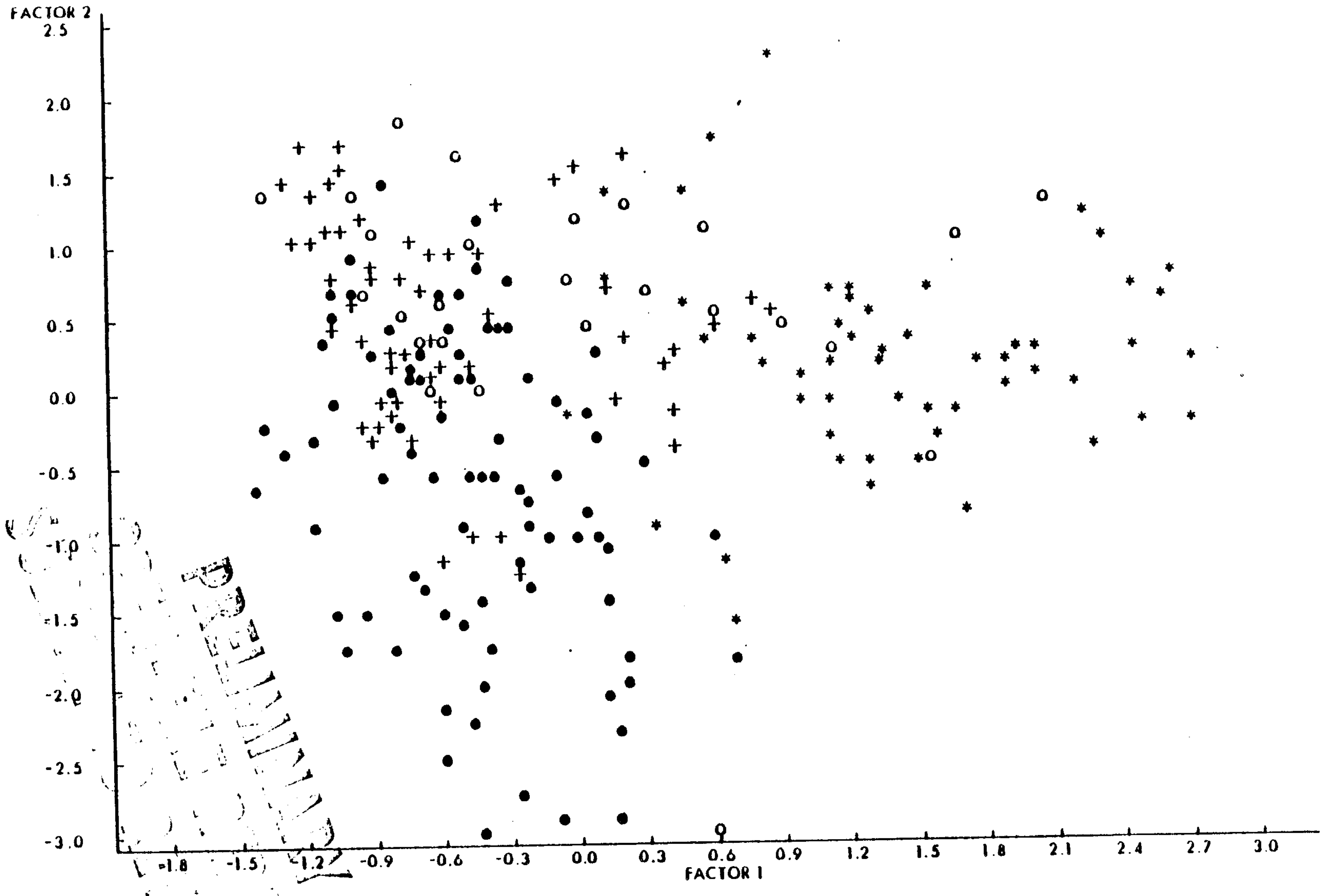

Figure 12. Mineralogical and petrophysical variables from Lincoln 1637 samples plotted on first two principal components. Symbols correspond to shale types defined by fabric: * thinly-laminated shale, o lenticularly laminated shale, • sharply-banded shale, + nonbanded shale. Compositional groups as plotted in figure 7 are generally dominated by specific fabric types.

COMPARISON OF COMPOSITIONAL AND PETROPHYSICAL VARIABLES

Introduction

Subdivision of the Devonian shale sequence into stratigraphic units (geophysical log response) and lithic types (fabric elements) is based on limited knowledge of their compositional and petrophysical properties. This chapter presents an analyses of the compositional and petrophysical variables measured on samples from Lincoln 1637, Jackson 1369, and Wise 253. Each well is discussed seperately with a comparison of the gas producing lower portion of the Huron Member given at the end of the chapter. Univariate analysis of variance and Duncan's Multiple Range Test were used in determining significant difference between lithic types and stratigraphic units.

Lincoln 1637

Lithic Types - Means and standard deviations of compositional and petrophysical variables are given in table 2. Results of the analysis of variance is presented in table 3. Of the 32 variables measured, 14 showed a significant difference (at the .05 level or higher) for at least one of the lithic types. Several variables showed slightly lower confidence levels, but after visual inspection of means and standard deviations, were concluded to be indicative of trends among the lithic types. Variables showing a difference for at least one of the lithic types are discussed below.

LOI 100 - Mean organic content is highest in thinly-laminated shale and lowest in nonbanded shale.

KAOLINITE - Mean values are highest in sharply-banded and thinly-laminated shale. This reflects the stratigraphic position of these lithic types in the upper part of the section and a subsequent change in source material.

Variable	SB (N=65)		TL (N=40)		LL (N=40)		NB (N=47)	
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
LOI 100	3.4	1.36	7.2	2.49	4.3	2.11	2.5	.86
14 A Clay	.7	.47	.6	.30	.8	.34	.9	.42
Illite	48.8	11.27	46.8	9.18	54.3	8.46	54.9	7.71
Quartz	33.5	5.53	35.6	6.59	31.0	4.44	31.6	4.16
Pyrite	4.9	3.85	7.8	7.80	6.4	5.35	2.7	2.54
Calcite	.7	1.90	.4	.61	.4	.85	.5	1.23
Dolomite	.4	.92	.6	1.24	.3	.49	.2	.55
Orthoclase	.3	.53	.4	.54	.3	.43	.3	.34
Plagioclase	3.3	1.86	2.3	1.76	1.9	.84	2.4	.91
Silt	23.3	13.80	14.4	5.81	10.9	4.20	12.2	4.42
Siderite	2.3	4.60	1.3	1.29	1.5	1.16	2.3	1.69
Bulk Density	2.69	4.38	2.54	.07	2.62	.09	2.67	.03
Matrix Density	2.73	4.74	2.59	.09	2.69	.10	2.74	.04
Porosity	1.44	1.08	2.24	1.69	2.88	1.10	2.40	1.26
Log Density	2.66	.04	2.54	.06	2.64	.23	2.60	.06
Sonic	77	4	87	5	84	5	82	5
Resistivity	37	11	93	75	35	45	30	30
Gamma Ray	195	15	278	58	243	94	229	51
S	2.0	1.30	2.7	1.18	2.4	2.35	1.2	.94
SiO_2	61.8	3.88	63.4	3.53	61.7	2.99	63.0	2.06
Al_2O_3	18.9	1.88	16.9	1.72	17.8	1.69	18.9	1.47
MgO	1.7	.24	1.6	.29	1.7	.30	1.8	.22
CaO	.4	.56	.7	.46	.7	.33	.8	.53
Na_2O	.8	.03	.8	.03	.8	.02	.8	.02
K_2O	4.1	.76	4.1	.62	4.7	.74	4.8	.60
TiO	1.2	.12	.9	.15	1.0	.19	1.1	.13
PO	.1	.10	.1	.02	.1	.03	.1	.02
Fe_2O_3	8.6	1.82	8.4	1.76	8.8	2.14	7.4	.98
Zn	87	25	122	118	80	67	85	90

Table 2. Means and standard deviations of compositional and petrophysical variables for: sharply-banded shale (SB), thinly-laminated shale (TL), lenticularly-laminated shale (LL) and nonbanded shale (NB) from Lincoln 1637.

Variable	PR>F	SB (N=65)	TL (N=40)	LL (N=40)	NB (N=47)
LOI 100	.0001*		H		L
Kaolinite	.0001*	H	H	L	L
14 A Clay	.0025*	L	L	H	H
Illite	.0675	L	L	H	H
Quartz	.0682	H	H	L	L
Pyrite	.0037*	L	H	H	L
Calcite	.5572				
Dolomite	.6167				
Siderite	.5811				
Gypsum	.5457				
Anhydrite	.4424				
Orthoclase	.2028				
Plagioclase	.6072				
Silt	.1466	H	H	L	L
Bulk Density	.0001*		L		
Matrix Density	.0001*		L		
Porosity	.1776				
Log Density	.1113		L		
Sonic	.1813	L			
Resistivity	.0002*		H		
Gamma Ray	.3269		H		
S	.0013*		H		L
SiO_2	.5328				
Al_2O_3	.0060*	L	L	H	H
MgO	.0429*				H
CaO	.2069				
Na_2O	.1182				
K_2O	.0080*	L	L	H	H
TiO	.0001*	H			
PO	.1884				
Fe_2O_3	.0045*				L
Zn	.0412*		H		

Table 3. Analysis of variance on lithic types from Lincoln 1637. An asterisk* denotes a significant difference (at the .05 level or higher) for at least one of the lithic types. Relative highs (H) and lows (L) for a given variable were determined from Duncan's multiple range test and visual inspection of the data.

14 Å CLAY - Mean chlorite content is highest in lenticularly-laminated and nonbanded shale.

ILLITE - Mean values are highest in lenticularly laminated and nonbanded shale.

QUARTZ - Mean values are highest in sharply-banded and thinly-laminated shale.

SILT - Mean values are highest in sharply-banded and thinly-laminated shale.

BULK DENSITY - Mean value is lowest in thinly-laminated shale because of its high organic matter content.

MATRIX DENSITY - Mean value is lowest in thinly-laminated shale because of its high organic matter content.

LOG DENSITY - Mean value is lowest in thinly-laminated shale because of its high organic matter content.

SONIC TRANSIT TIME - Mean value is highest in thinly-laminated shale because of its high organic matter content.

RESISTIVITY - Mean value is highest in thinly-laminated shale because of its high organic matter content.

GAMMA RAY - Mean value is tending to be higher in thinly-laminated shale because of the association between organic matter and uranium in anoxic sediments.

SULFUR (S) - Mean value is highest in thinly-laminated shale because of its high pyrite content.

ALUMINUM (Al_2O_3) - Mean values are highest in lenticularly-laminated and nonbanded shales because they have the highest clay content.

MAGNESIUM (MgO) - Mean value is highest in nonbanded shale possibly because of its higher chlorite content.

POTASSIUM (K_2O) - Mean values are highest in lenticularly-laminated and nonbanded shales because they have the highest illite content.

TITANIUM (TiO) - Mean value is highest in sharply-banded shale possibly because of a greater abundance of titanium bearing heavy minerals.

IRON (Fe_2O_3) - Mean value is lowest in nonbanded shale because it has the lowest pyrite content.

ZINC (Zn) - Mean value is highest in thinly-laminated shale likely reflecting the absorption of zinc on organic matter in a reducing environment.

The analysis of variance and multiple range tests generally seperated the organic rich lithic types from the organic poor lithic types. It is important to note that many minerals commonly used in environmental interpretation (carbonates and sulfates) show no differences among the lithic types. The bulk mineralogy of the lithic types is similar with pyrite showing the greatest variation. Geophysical log response is most effective in distinguishing thinly-laminated shale due to the large effect of organic matter on log response. Matrix porosity does not vary significantly among the lithic types.

Stratigraphic Units - Means and standard deviations of the six stratigraphic units recognized in Lincoln 1637 are given in table 4. Results of the analysis of variance is given in table 5. As can be seen from the stratigraphic distribution of the lithic types (Table 6), many stratigraphic units are dominated by one or two lithic types. Of the 32 variables measured, 15 show a significant difference (at the .05 level or higher) for at least one of the stratigraphic units. Several variables, such as quartz and illite, show slightly higher confidence levels, but after visual inspection of means and standard deviations were concluded to represent trends among stratigraphic units. Variables showing a difference for at least one of the stratigraphic units are discussed below.

Variable	UDS (N=26)		UMH (N=65)		LH (N=44)		JF (N=9)		AS (N=13)		RS (N=39)	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
LOI 100	3.1	1.35	3.5	1.77	5.7	2.96	2.2	.74	2.6	.97	4.8	2.98
Kaolinite	.9	.27	.6	.31	.4	.21	0	0	.2	.52	.3	.72
14 A Clay	.8	.41	.8	.40	.7	.26	.9	.43	.9	.33	.8	.48
Illite	46.8	9.91	47.7	11.92	46.9	8.87	55.7	7.35	58.1	6.47	54.8	8.48
Quartz	35.9	5.58	33.7	5.28	35.4	6.19	32.2	4.03	29.7	3.92	31.3	5.11
Pyrite	4.8	3.20	4.5	3.85	7.2	7.84	3.3	2.79	2.4	2.22	5.2	5.60
Calcite	.6	.84	.9	2.71	.6	1.29	.3	.49	.8	.91	.4	.64
Dolomite	.3	.46	.7	1.52	.5	1.16	0	0	.3	.42	.3	.73
Siderite	1.6	1.42	3.0	5.01	1.5	1.41•	1.4	1.02	2.3	1.80	1.6	1.05
Orthoclase	.3	.48	.3	.49	.3	.52	.4	.47	.4	.29	.3	.38
Plagioclase	4.2	1.96	3.2	1.78	2.5	.63	2.8	.75	2.7	.96	2.3	.82
Gypsum	.3	.36	.4	.51	.3	.44	.4	.48	.3	.31	.3	.41
Anhydrite	.3	.42	.4	.64	.5	.69	.1	.21	.3	.31	.6	.79
Silt	32.4	15.20	20.1	14.01	16.2	4.96	11.9	3.97	10.9	2.15	9.5	3.45
Bulk Density	2.70	.03	2.69	.04	2.58	.09	2.66	.02	2.65	.02	2.61	.09
Matrix Density	2.73	.03	2.72	.05	2.63	.09	2.71	.05	2.72	.03	2.69	.12
Porosity	1.32	1.08	1.36	1.02	2.42	1.56	1.97	1.36	2.78	.89	2.83	1.34
Log Density	2.69	.03	2.65	.03	2.53	.05	2.63	.01	2.65	.01	2.60	.18
Sonic	74	3	79	3	87	4	78	3	78	1	86	6
Resistivity	30	6	40	13	83	57	14	2	11	2	50	72
Gamma Ray	185	13	199	15	284	48	210	35	188	13	252	83
S	1.7	1.24	1.9	2.15	2.5	.84	1.3	.86	.7	.78	2.6	2.58
SiO_2	65.1	4.27	63.4	3.80	65.5	2.04	63.7	1.53	62.6	1.25	63.7	3.18
Al_2O_3	18.9	2.36	18.9	2.65	17.8	1.78	18.9	.75	19.1	.59	18.1	1.60
MgO	1.6	.24	1.8	.25	1.7	.25	1.8	.11	1.9	.18	1.7	.32
CaO	.3	.33	.9	2.15	.7	.50	.7	.33	.9	.60	.8	.39
Na_2O	.8	.03	.8	.05	.8	.03	.8	.02	.8	.01	.8	.03
K_2O	3.8	.96	4.2	.96	4.2	.51	4.6	.27	5.2	.30	5.0	.67
TiO	1.3	.11	1.2	.14	1.0	.11	1.2	.11	1.2	.05	.9	.18
PO	.1	.01	.1	.07	.1	.02	.1	.01	.1	.03	.1	.01
Fe_2O_3	8.1	1.45	8.7	2.08	8.1	1.17	7.9	1.26	8.0	.94	8.7	2.84
Zn	94	32	94	74	100	72	65	18	59	8	94	119

Table 4. Means and standard deviations of compositional and petrophysical variables for: undifferentiated Devonian shale (UDS), upper-middle Huron (UMH), lower Huron (LH), Java Formation (JF), Angola Shale Member (AS) and Rhinstreet Shale Member (RS). From Lincoln 1637.

Variable	PR>F	UDS	UMH	LH	JF	AS	RS
LOI 100	.0301*			H			H
Kaolinite	.2890						
14 A Clay	.7471						
Illite	.0557				H	H	H
Quartz	.0548	H	H	H			
Pyrite	.0313*			H			H
Calcite	.7980						
Dolomite	.9400						
Siderite	.2213						
Gypsum	.4794						
Anhydrite	.5772						
Orthoclase	.5529						
Plagioclase	.1391	H					
Silt	.0001*	H	H				
Bulk Density	.0001*			L			L
Matrix Density	.0001*			L			L
Porosity	.0039*					H	H
Log Density	.0010*			L			L
Sonic	.0001*			H			H
Resistivity	.0401*			H			H
Gamma Ray	.0001*			H			H
S	.1237			H			H
SiO_2	.2235	H		H			
Al_2O_3	.1851					H	
MgO	.0204*	L					
CaO	.0063*	L					
Na_2O	.9716						
K_2O	.0002*				H	H	H
TiO	.0001*	H					L
PO	.0016*	L					
Fe_2O_3	.5863						
Zn	.2368						

Table 5. Analysis of variance on stratigraphic units from Lincoln 1637. An asterisk (*) denotes a significant difference (at the 0.5 level or higher) for at least one of the stratigraphic units. Relative highs (H) and lows (L) for a given variable were determined from Duncan's multiple range test and visual inspection of the data.

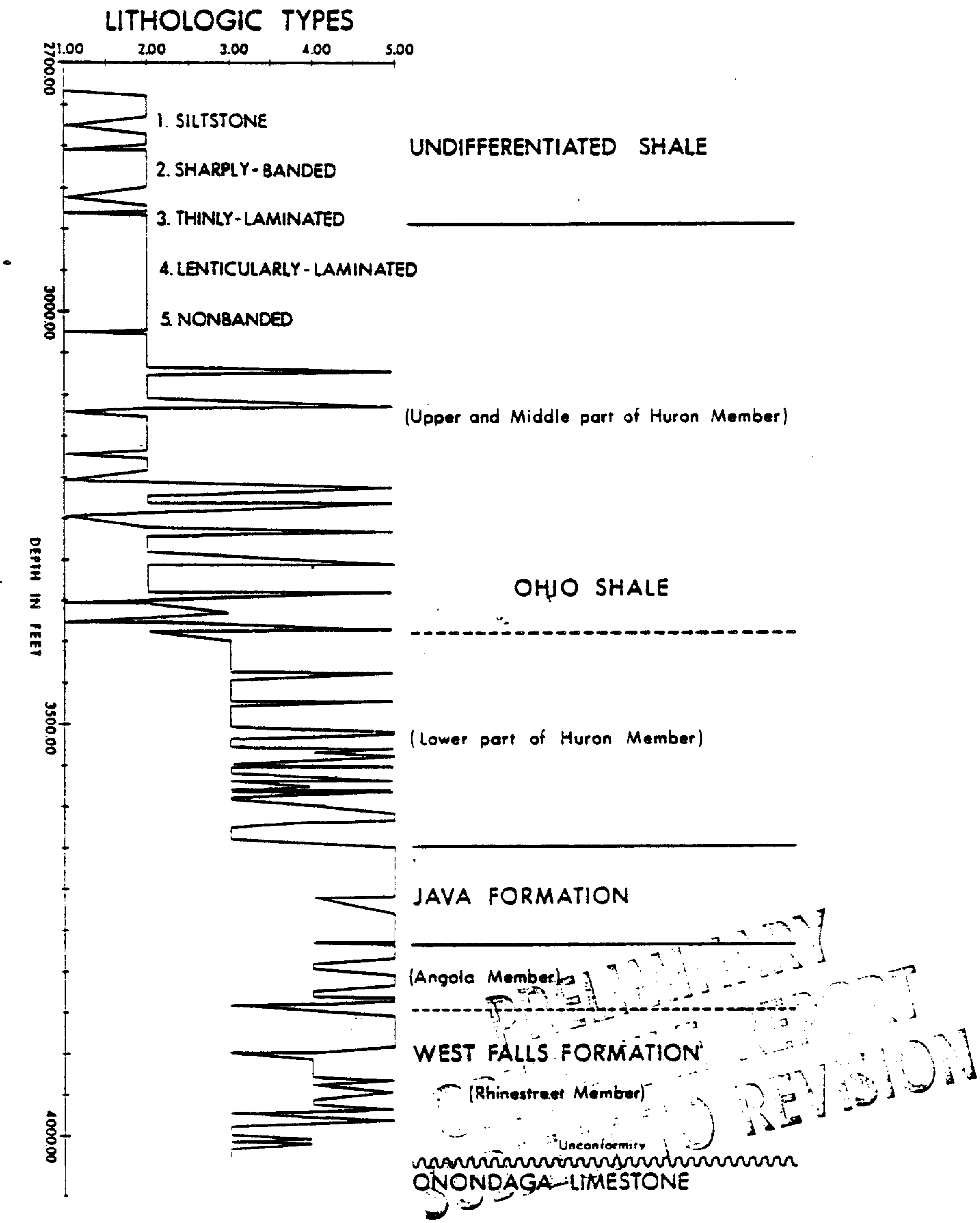

Table 6. Stratigraphic distribution of lithic types in Lincoln 1637.

LOI 100 - Mean values are highest in the lower Huron and Rhinestreet because they contain more thinly-laminated shale.

ILLITE - Mean values are highest in the Java Fm., Angola Shale, and Rhinestreet.

QUARTZ - Mean values are highest in the undifferentiated Devonian shales, upper-middle Huron and lower Huron.

PYRITE - Mean values are highest in the lower Huron and Rhinestreet because they contain more organic rich shale.

PLAGIOCLASE - Mean value is relatively higher in the undifferentiated Devonian shales.

SILT - Mean values are highest in the undifferentiated Devonian shales and the upper-middle Huron. A general trend of increasing silt content upsection is present in Lincoln 1637.

BULK, MATRIX, LOG DENSITY - Mean values are lowest in the lower Huron and Rhinestreet because of their higher organic content.

SONIC TRANSIT TIME, RESISTIVITY, GAMMA RAY - Mean values are highest in the lower Huron and Rhinestreet because of their higher organic content.

POROSITY - Mean values are highest in the Angola Shale and Rhinestreet.

SULFUR (S) - Mean values are highest in the lower Huron and Rhinestreet because of their higher pyrite content.

SILICON (SiO_2) - Mean values are highest in the undifferentiated Devonian shales and lower Huron.

ALUMINUM (Al_2O_3) - Mean value is highest in the Angola Shale.

MAGNESIUM (MgO) - Mean value is lowest in the undifferentiated Devonian shales.

CALCIUM (CaO) - Mean value is lowest in the undifferentiated Devonian shales.

POTASSIUM (K_2O) - Mean values are highest in the Java Fm., Angola Shale, and Rhinestreet because of their higher illite content.

TITANIUM (TiO) - Mean value is lowest in the Rhinestreet and highest in the undifferentiated Devonian shales. This may reflect the distribution of heavy minerals in the shale sequence.

PHOSPHOROUS (PO) - Mean value is lowest in the undifferentiated Devonian shales.

As can be seen from the analysis of variance table,the lower Huron and Rhinestreet are generally differentiated from the other stratigraphic units. The higher organic content of these two units causes the low density and other log responses used in their recognition in the subsurface. Little difference in bulk mineralogy is present among the stratigraphic units in this well. Depositional models of the shale sequence that invoke drastic changes in water depth or source material do not seem to be applicable. A measure of the energy level (measured by relative amounts of quartz and illite) in black and gray shale environments shows little difference. A trend of increasing silt upsection probably reflects the westward progradation of the Catskill deltaic complex.

Jackson 1369

Lithic Types - Analysis of mineralogical and petrophysical data from Jackson 1369 is restricted to the lower portion of the Huron member as it was the only unit cored in the well. All four of the previously described shale lithic types are present in sufficient numbers for statistical analysis. Means and standard deviations of the measured variables are given in table 7. Results of the analysis of variance is presented in table 8. Of the 32 variables measured, 11 showed a significant difference for at least one of the lithic types at the .05 level or higher. Additional variables showed slightly lower confidence levels, but after visual inspection of means and standard deviations, were concluded to be indicative of trends among the lithic types.

Variable	SB (N=6)		TL (N=13)		LL (N=11)		NB (N=10)	
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
LOI 100	3.7	1.26	5.8	1.13	5.1	1.38	3.4	1.00
14 A Clay	1.0	.39	1.0	2.61	1.1	2.45	1.1	.25
Illite	57.8	9.13	56.8	8.32	61.2	4.59	58.5	10.30
Quartz	28.5	5.98	30.7	6.36	26.3	3.83	29.3	7.03
Pyrite	5.8	.92	5.3	.65	4.0	1.65	2.5	1.38
Calcite	.5	.51	.6	.93	1.6	4.45	.9	.92
Dolomite	.3	.62	.2	.54	.2	.48	.6	1.30
Siderite	.4	.51	1.0	.84	.9	.52	2.4	3.12
Orthoclase	.1	.22	.2	.41	.1	.17	.1	.29
Plagioclase	3.5	2.01	2.4	.49	3.0	.91	2.9	1.51
Gypsum	.4	.69	.3	.33	.2	.23	.2	.34
Anhydrite	.2	.34	.2	.46	.2	.35	.4	.44
Silt	13.2	4.99	12.9	2.69	13.0	2.75	13.2	4.98
Bulk Density	2.70	.06	2.60	.06	2.63	.07	2.70	.02
Matrix Density	2.72	.05	2.63	.06	2.66	.06	2.73	.03
Porosity	1.09	1.06	1.26	.87	1.50	.94	.99	.02
Log Density	2.63	.05	2.58	.05	2.58	.03	2.63	.07
Sonic	78	5	84	4	82	5	82	4
Resistivity	36	10	90	63	46	7	28	25
Gamma Ray	200	18	237	29	253	53	209	39
S	2.0	1.08	2.6	.43	2.3	1.22	1.5	.74
SiO_2	62.9	2.41	65.9	1.15	65.5	2.14	65.6	2.47
Al_2O_3	20.0	1.53	17.2	.69	17.9	.88	18.5	1.68
MgO	1.9	.08	1.8	.13	1.9	.10	1.9	.11
CaO	.2	.08	.5	.34	.4	.13	.6	.46
K_2O	4.8	.52	4.0	.33	4.3	.38	4.3	.63
TiO	1.2	.09	1.1	.08	1.0	.08	1.2	.11
PO	.1	.03	.1	.01	.1	.01	.1	.02
Fe_2O_3	8.1	1.80	8.6	.73	8.0	1.81	7.1	1.25
Zn	75	18	72	31	138	187	77	24

Table 7. Means and standard deviations of compositional and petrophysical variables for: sharply-banded shale (SB), thinly-laminated shale (TL), lenticularly-laminated shale (LL), and nonbanded shale (NB) from Jackson 1369.

Variable	PR>F	SB (N=6)	TL(N=13)	LL (N=11)	NB(N=10)
LOI 100	.0002*	L	H	H	L
Kaolinite	.2498				
14 A Clay	.1079				
Illite	.0275*			H	
Quartz	.0201*			L	
Pyrite	.0495*	H	H	H	L
Calcite	.3768				
Dolomite	.6753				
Siderite	.4487				
Gypsum	.4697				
Anhydrite	.2880				
Orthoclase	.5781				
Plagioclase	.4136				
Silt	.3820				
Bulk Density	.0001*	H	L	L	H
Matrix Density	.0003*	H	L	L	H
Porosity	.0876				L
Log Density	.1801	H	L	L	H
Sonic	.2487				
Resistivity	.0463*		H		
Gamma Ray	.2281		H	H	
S	.0396*	H	H	H	L
SiO_2	.0223*	L			
Al_2O_3	.0003*	H			
MgO	.2228				
CaO	.2523				
Na_2O	.2306				
K_2O	.0257*	H	L		
TiO	.0001*			L	
PO	.3585				
Fe_2O_3	.0994	H	H	H	L
Zn	.3592				

Table 8. Analysis of variance on lithic types from Jackson 1369. An asterisk (*) denotes a significant difference (at the .05 level or higher) for at least one of the lithic types. Relative highs (H) and lows (L) for a given variable were determined from Duncan's multiple range test and visual inspection of the data.

Variables showing a difference for at least one of the lithic types are discussed below.

LOI 100 - Mean values are highest in thinly-laminated and lenticularly-laminated shale.

ILLITE - Mean value is highest in lenticularly-laminated shale.

QUARTZ - Mean value is lowest in lenticularly-laminated shale

PYRITE - Mean values are highest in sharply-banded, lenticularly-laminated and thinly-shales because they contain more organic matter

BULK, MATRIX, LOG DENSITY - Mean values are lowest in thinly-laminated and lenticularly-laminated shale because of their higher organic content.

RESISTIVITY, GAMMA RAY - Mean values are highest in thinly-laminated and lenticularly-laminated shale because of their higher organic content.

POROSITY - Mean value is lower in nonbanded shale although the difference is less than .5%.

SULFUR (S) - Mean values are highest in sharply-banded, lenticularly-laminated, and thinly-laminated shale because of their higher pyrite content.

SILICON (SiO_2) - Mean value is lowest in sharply-banded shale.

ALUMINUM (Al_2O_3) - Mean value is highest in sharply-banded shale.

POTASSIUM (K_2O) - Mean value is highest in sharply-banded shale.

TITANIUM (TiO_2) - Mean value is lowest in lenticularly-laminated shale.

IRON (Fe_2O_3) - Mean value is lowest in nonbanded shale because of its lower pyrite content.

In the lower portion of the Huron Member in Jackson 1369, the principal compositional difference between the lithic types is organic matter, with the thinly-laminated and lenticularly-laminated lithic types having the highest organic content. Pyrite content is also high reflecting the reducing environment produced by large quantities of organic matter. Differences in illite and quartz contents are small, when present, (2-3%) and do not suggest a significant change in the energy level of the organic-rich and organic-poor shale environments. No differences appear in carbonate, sulfate, feldspar or silt contents. The lack of significant differences in black and gray shale mineralogy indicates that changes in the factors controlling the rate of production or preservation of plant material were important in producing a black or gray shale environment. Factors such as water depth, circulation, rate of nutrient supply may be important. Apparently, a delicate balance existed between the capacity of the environment to produce organic matter and the capacity of the environment to degrade it. A small shift towards increased plant production or preservation produced the black shales.

Wise 253

Lithic Types - Means and standard deviations of compositional and petrophysical variables are given in table 9. Results of the analysis of variance are presented in table 10. Of the 32 variables measured, only 4 showed a significant difference (at the .05 level or higher) for at least one of the lithic types. This is a much lower number than for the other two study wells. Variables showing a difference for at least one of the lithic types are discussed below.

LOI 100 - Mean organic content is lowest in nonbanded shale, because of bioturbation. Sharply-banded, thinly-laminated and lenticularly-laminated shales show no difference in mean organic content.

14 Å CLAY - Mean values are highest in lenticularly-laminated and nonbanded shale.

Variable	SB (N=15)		TL (N=23)		LL (N=15)		NB (N=15)	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
LOI 100	4.9	2.13	4.5	1.67	4.5	2.10	3.4	2.27
14 A Clay	.7	.28	.7	.33	.9	.34	.8	.34
Illite	42.3	8.28	41.6	8.11	42.8	10.86	44.8	8.80
Quartz	35.1	3.36	35.9	3.23	35.0	4.23	34.3	2.28
Pyrite	9.4	5.47	8.7	3.49	9.5	4.46	9.2	7.58
Calcite	.2	.16	.2	.17	.2	.16	.1	.11
Dolomite	.2	.61	.6	.20	.2	.66	.4	1.04
Siderite	3.2	2.21	3.4	1.51	3.4	1.84	3.1	1.58
Orthoclase	.1	.05	.1	.08	.1	.10	.1	.06
Plagioclase	2.7	1.92	2.9	2.33	2.7	1.40	2.0	.63
Gypsum	0	0	0	0	0	0	0	0
Anhydrite	.7	.61	.6	.67	.6	.57	.7	.58
Silt	21.1	7.22	20.3	10.27	20.9	7.69	16.9	8.01
Bulk Density	2.59	.09	2.60	.05	2.63	.08	2.69	.06
Matrix Density	2.68	.07	2.68	.04	2.70	.07	2.75	.05
Porosity	2.99	1.52	2.67	1.13	2.68	1.47	2.29	1.27
Log Density	2.56	.06	2.58	.06	2.59	.06	2.58	.06
Sonic	75	6	85	7	80	5	83	5
Resistivity	34	11	32	14	28	11	36	16
Gamma Ray	233	43	223	55	227	45	253	69
S	2.8	1.84	2.6	.84	3.2	1.66	3.1	2.40
SiO_2	63.7	2.77	65.2	4.26	63.3	3.46	63.4	1.94
Al_2O_3	18.4	2.01	16.9	2.20	17.7	1.26	17.6	2.96
MgO	1.5	.32	1.6	.34	1.5	.25	1.7	.29
CaO	.5	.46	.5	.62	.3	.32	.5	.38
K_2O	4.2	.57	3.9	.94	4.1	.69	4.1	.91
TiO	1.1	.15	.9	.14	1.0	.13	1.2	.14
PO	.1	.02	.1	.02	.1	.12	.1	.01
Fe_2O_3	7.1	1.94	7.0	1.95	7.8	2.06	7.7	2.34
Zn	201	253	128	163	116	140	359	759

Table 9. Means and standard deviations of compositional and petrophysical variables for: sharply-banded shale (SB), thinly-laminated shale (TL), lenticularly-laminated shale (LL), and nonbanded shale (NB) from Wise 253.

Variable	PR>F	SB (N=15)	TL (N=23)	LL (N=15)	NB(N=47)
LOI 100	.0812	H	H	H	L
Kaolinite	.4457				
14 A Clay	.0043*	L	L	H	H
Illite	.5753				
Quartz	.2148				
Pyrite	.3592				
Calcite	.2389				
Dolomite	.1789				
Siderite	.2021				
Gypsum	.3378				
Anhydrite	.5498				
Orthoclase	.3765				
Plagioclase	.1570				
Silt	.4882				
Bulk Density	.0001*	L	L	L	H
Matrix Density	.0004*	L	L	L	H
Porosity	.1336				
Log Density	.0361*	L	H	H	H
Sonic	.2367				
Resistivity	.3857				
Gamma Ray	.6266				
S	.4667				
SiO_2	.6403				
Al_2O_3	.3784				
MgO	.1681				
CaO	.6874				
Na_2O	.5796				
K_2O	.7781				
TiO	.6036				
PO	.6232				
$Fe2O_3$	.8198				
Zn	.2535				

Table 10. Analysis of variance on lithic types from Wise 253. An asterisk (*) denotes a significant difference (at the .05 level or higher) for at least one of the lithic types. Relative highs (H) and lows (L) for a given variable were determined from Duncan's multiple range test and visual inspection of the data.

BULK, MATRIX DENSITY - Mean values are highest in nonbanded shale because of its lower organic content.

LOG DENSITY - Mean value is lowest in sharply-banded shale because of its higher organic content.

The analysis of variance and multiple range tests only seperated the nonbanded shales by virtue of their lower organic content. No minerals (except for chlorite) showed a difference between the lithic types. Matrix porosity does not vary significantly among the lithic types.

Stratigraphic Units - Means and standard deviations of the three stratigraphic units cored in Wise 253 are given in table 11. Results of the analysis of variance are given in table 12. Of the 32 variables measured, 17 show a significant difference (at the .05 level or higher) for at least one of the stratigraphic units. This is a much higher number than for the lithic types. Variables showing a difference for at least one of the stratigraphic units are discussed below.

LOI 100 - Mean organic contents are higher in the Three Lick Bed and lower Huron.

14 A CLAY - Mean chlorite content is lowest in the Three Lick Bed.

ILLITE - Mean value is lowest in the Three Lick Bed. This unit is above the Huron Member and the lower illite content probably reflects progradation of delta complexes into the basin.

QUARTZ, PLAGIOCLASE, SILT - Mean values are highest in the Three Lick Bed reflecting progradation of delta complexes into the basin.

BULK, MATRIX, LOG DENSITY - Mean values are lowest in the lower Huron because it has the highest organic content.

RESISTIVITY, GAMMA RAY - Mean values are highest in the lower Huron because it has the highest mean organic content of the three stratigraphic units.

Variable	TLB (N=20)		UMH (N=11)		LH (N=36)	
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
LOI 100	4.3	1.72	2.9	.83	4.4	2.10
14 A Clay	.6	.35	1.0	.28	.9	.29
Illite	37.5	9.60	46.5	5.54	44.6	8.31
Quartz	37.5	3.41	33.9	1.89	34.2	2.99
Pyrite	10.6	7.99	7.8	2.04	8.6	4.08
Calcite	.2	.17	.2	.13	.2	.15
Dolomite	.2	.60	0	0	.6	1.77
Siderite	3.1	1.77	3.9	2.07	3.3	1.73
Orthoclase	.1	.07	.1	.05	.1	.08
Plagioclase	3.7	2.61	1.9	.56	2.0	.83
Gypsum	0	0	0	0	0	0
Anhydrite	.8	.61	.4	.53	.7	.54
Silt	27.6	9.46	18.9	7.49	15.4	4.72
Bulk Density	2.64	.08	2.66	.03	2.63	.07
Matrix Density	2.71	.08	2.72	.02	2.70	.05
Porosity	2.62	1.29	1.96	1.21	2.77	1.45
Log Density	2.58	.08	2.64	.02	2.58	.04
Sonic	79	6	81	4	83	5
Resistivity	32	11	20	3	36	15
Gamma Ray	187	24	188	10	271	47
S	2.9	2.63	2.6	.42	3.0	1.26
SiO_2	68.1	4.75	64.1	.81	64.9	2.54
Al_2O_3	17.2	3.26	19.3	.61	18.3	1.51
MgO	1.4	.26	1.7	.19	1.8	.21
CaO	.6	.57	.1	.01	.5	.49
K_2O	3.5	1.07	4.6	.29	4.5	.49
TiO	1.1	.17	1.2	.09	1.1	.09
PO	.1	.02	.1	.01	.1	.02
Fe_2O_3	7.1	2.89	8.1	.74	7.9	1.62
Zn	234	700	103	36	205	323

Table 11. Means and standard deviations of compositional and petrophysical variables for the Three Lick Bed (TLB), upper-middle Huron (UMH), and lower Huron (LH) from Wise 253.

Variable	PR>F	TLB (N=20)	UMH (N=11)	LH (N=40)
LOI 100	.0054*	H	L	H
Kaolinite	.4635			
14 A Clay	.0004*	L	H	H
Illite	.0138*	L	H	H
Quartz	.0022*	H	L	L
Pyrite	.2678			
Calcite	.3340			
Dolomite	.0001		L	
Siderite	.4900			
Gypsum	.3765			
Anhydrite	.2962			
Orthoclase	.8867			
Plagioclase	.0007*	H	L	L
Silt	.0004*	H	L	L
Bulk Density	.0091*	H	H	L
Matrix Density	.0064*	H	H	L
Porosity	.2296			
Log Density	.0001*	L	H	L
Sonic	.2456			
Resistivity	.0107*	H	L	H
Gamma Ray	.0001*	L	L	H
S	.5755			
SiO_2	.0026*	H	L	L
Al_2O_3	.1169	L	H	H
MgO	.0001*	L	H	H
CaO	.0801	H	L	H
Na_2O	.9124			
K_2O	.0001*	L	H	H
TiO	.1750			
PO	.1500			
Fe_2O_3	.1853			
Zn	.9079			

Table 12. Analysis of variance on stratigraphic units from Wise 253. An asterisk (*) denotes a significant difference (at the .05 level or higher) for at least one of the stratigraphic units. Relative highs (H) and lows (L) for a given variable were determined from Duncan's multiple range test and visual inspection of the data.

SILICON (SiO_2) - Mean value is highest in the Three Lick Bed because it has the highest quartz content.

ALUMINUM (Al_2O_3) - Mean values are highest in the upper-middle and lower Huron because they have higher illite contents than the Three Lick Bed.

MAGNESIUM - Mean values are highest in the upper-middle Huron and lower Huron probably due to their higher chlorite content.

CALCIUM - Mean value is lowest in the upper-middle Huron because of its low dolomite content.

POTASSIUM (K_2O) - Mean value is lowest in the Three Lick Bed because of its lower illite content.

As can be seen from the analysis of variance table, the lower Huron and the Three Lick Bed are differentiated from the upper-middle Huron on the basis of their higher organic contents. The higher organic content of these two units causes the low density and other log responses used in their recognition in the subsurface. In addition the Three Lick Bed is differentiated from the upper-middle Huron and the lower Huron by a higher quartz, plagioclase and silt content.

Comparison of Gas Producing Lower Huron In
Wise 253, Lincoln 1637 and Jackson 1369

The lower portion of the Huron Member was productive in all three study wells. Wise 253 had a natural open flow of 0 MCFD, but produced at a modest rate after stimulation. The lower Huron in Lincoln 1637 had a natural open flow of 98 MCFD and a final open flow of 200 MCFD after stimulation. Jackson 1369 had a natural open flow of 1007 MCFD from the lower Huron. Since these three wells had varying gas yield and were widely spaced geographically, it is appropriate to the compare the compositional and petrophysical parameters of the three wells to see if any relationship to gas yield is evident. Means and standard deviations of compositional and petrophysical parameters are given in table 13. Results of the analysis of variance are presented in table 14. Of the 32 variables measured,17 showed a significant difference (at the 0.05 level or higher) for at least one of the wells. Variables showing a difference for at least one of the wells are discussed below.

LOI 100 - Mean values are lowest (and the same) for the lowest producing well (Wise 253) and the highest producing well (Jackson 1369) suggesting that organic content is not important once a minimum level for gas generation is reached.

14 A CLAY - The highest producing well had the highest chlorite content, but this likely reflects regional differences in sediment source and is not related to higher gas production.

ILLITE - Mean value is greatest in the highest producing well suggesting that minor differences in shale mineralogy do not effect gas production.

QUARTZ, PYRITE - Mean values are highest in the lowest producing wells indicating that the mineralogy of the shale does not effect gas production.

Variable	Wise 253 $\bar{x}$	Wise 253 σ	Linc 1637 $\bar{x}$	Linc 1637 σ	Jack 1369 $\bar{x}$	Jack 1369 σ
LOI 100	4.4	2.10	5.7	2.96	4.5	1.62
14 Å Clay	.9	.29	.4	.21	1.0	.25
Illite	44.6	8.31	46.9	8.87	57.2	10.68
Quartz	34.2	2.99	35.4	6.19	29.6	6.80
Pyrite	8.6	4.08	7.2	7.84	4.1	1.74
Calcite	.2	.15	.6	1.29	.9	2.40
Dolomite	.6	1.77	.5	1.16	.4	.83
Siderite	3.3	1.73	1.5	1.41	1.2	1.76
Orthoclase	.1	.08	.3	.52	.2	.31
Plagioclase	2.0	.83	2.5	.63	3.0	1.23
Gypsum	0	0	.3	.44	.2	.37
Anhydrite	.7	.54	.5	.69	.2	.40
Silt	15.4	4.72	16.2	4.96	14.5	8.06
Bulk Density	2.63	.07	2.58	.09	2.65	.07
Matrix Density	2.70	.05	2.63	.09	2.68	.06
Porosity	2.77	1.05	2.42	1.56	1.25	.83
Log Density	2.58	.04	2.53	.05	2.61	.06
Sonic	83	5	87	4	81	4
Resistivity	36	15	83	57	44	18
Gamma Ray	271	47	284	48	228	43
S	3.0	1.26	2.5	.84	2.15	.88
SiO_2	64.9	2.54	65.5	2.04	65.3	2.02
Al_2O_3	18.3	1.51	17.8	1.78	18.1	1.39
MgO	1.8	.21	1.7	.25	1.8	.11
CaO	.5	.49	.7	.50	.4	.31
K_2O	4.5	.49	4.2	.51	4.3	.51
TiO	1.1	.09	1.0	.11	1.1	.09
PO	.1	.02	.1	.02	.1	.01
Fe_2O_3	7.9	1.62	8.1	1.77	8.0	1.39
Zn	205	323	100	72	91	102

Table 13. Means and standard deviations of compositional and petrophysical variables for; Wise 253 (0 MCFD - natural open flow), Lincoln 1637 (98 - MCFD - natural open flow) and Jackson 1369 (1007 MCFD - natural open flow). Data for each well are from the lower portion of the Huron Member.

Variable	PR>F	Wise 253	Linc 1637	Jack 1369
LOI 100	.0040*	L	H	L
14 Å Clay	.0001*	L	L	H
Illite	.0080*	L	L	H
Quartz	.0025*	H	H	L
Pyrite	.0010*	H	H	L
Calcite	.0420*	L	H	H
Dolomite	.2876			
Siderite	.0047*	H	L	L
Orthoclase	.1840			
Plagioclase	.0940			
Gypsum	.0001*	L		
Anhydrite	.6684			
Silt	.1044			
Bulk Density	.0050*	H	L	H
Matrix Density	.0040*	H	L	H
Porosity	.0001*	H	H	L
Log Density	.0060*	H	L	H
Sonic	.0045*	L	H	L
Resistivity	.0001*	L	H	L
Gamma Ray	.0050*	L	H	L
S	.0001*	H	L	L
SiO_2	.1684			
Al_2O_3	.2236			
MgO	.3464			
CaO	.4580			
K_2O	.3620			
TiO	.8846			
PO	.4684			
Fe_2O_3	.3786			
Zn	.0040*	H	L	L

Table 14. Analysis of variance on the lower portion of the Huron Member from Wise 253 (natural open flow-0 MCFD), Lincoln 1637 (natural open flow-98 MCFD), and Jackson 1369 (natural open flow-1007 MCFD). An asterisk (*) denotes a significant difference (at the .05 level or higher) for at least one of the wells.

CALCITE - Mean values were highest in Lincoln 1637 and Jackson 1369. Most of the calcite cemented siltlenses and siltstones in these wells. It was not in the form of fracture fillings.

SIDERITE - Mean value was highest in Wise 253. Siderite ocurred as a cement in siltstones, isolated crystals in the matrix, and concretions. It did not cement fractures.

GYPSUM - Mean value was lowest in Wise 253. No relation is gas yield exists.

BULK, MATRIX, LOG DENSITY - Mean values were lowest in Lincoln 1637 as that well had the highest organic content.

SONIC TRANSIT TIME, RESISTIVITY, GAMMA RAY - Mean values were highest in Lincoln 1637 due to its higher organic content.

POROSITY - Matrix porosity was lowest in the highest yielding well suggesting that the matrix porosity of the Devonian shales is not an important variable in well yield.

SULFUR (S) - Mean value was greatest in the lowest producing well (Wise 253). No direct relationship to gas production exists.

ZINC (Zn) - Mean value was greatest in the lowest producing well (Wise 253). No direct relationship to gas production exists.

The above analysis of three widely seperated Devonian gas-shale wells suggests that variations in the mineralogical and elemental composition of the black shales of the magnituded present in western West Virginia and Virginia cannot be related to well yield. Open fractures observed in the core were of primary importance in gas production from the lower Huron. A detailed discussion of natural fractures observed in core samples is presented in the following chapter.

EXAMINATION OF FRACTURES IN SHALE CORES

Economic gas production from the Devonian black shales of the Appalachian Basin is dependent on the presence of natural or induced fractures in the rock matrix (Hunter and Young, 1953). Fractographic logging of five Devonian shale cores revealed that there is not a one to one correspondence between natural fractures observed in the cores and gas shows detected by temperature and siblilation logs. The purpose of this chapter is to describe the characteristics of natural fractures associated with gas shows in the Devonian shale section.

Five wells in western West Virginia and Virginia provided approximately 2200 feet of core which served as the sample base for this study. The wells had varying natural open flows: 1) Jackson 1371-0 MCFD, 2) Jackson 1369-1007 MCFD, 3) Mason 146-200 MCFD, 4) Lincoln 1637-198 MCFD, 5) Wise 253-0 MCFD. Lincoln 1637 is the only well in which the entire Devonian shale sequence present in western West Virginia was cored and recovered. According to Schwietering (1979), the sequence is Upper Devonian in age and consists of the West Falls, Java, and Ohio Shale Formations. The black shale interval in the lower portion of the Huron Member of the Ohio Shale is the principal gas producing unit in the Devonian shale sequence of the Appalachian Basin. The remaining wells had cores of intervals which had gas shows before or after stimulation.

Lincoln 1637 and Jackson 1369 are located over the Rome Trough or on flanking faults at its margin (Fig. 13). The Rome Trough is a 500 mile long basement graben extending from northern Pennsylvania to central Kentucky (Harris, 1979). Wise 253 is located on the Pine Mountain thrust plate. Mason 146 and Jackson 1371 are not associated with any well defined detached or basement sturcture. None of the wells are located on anticlines.

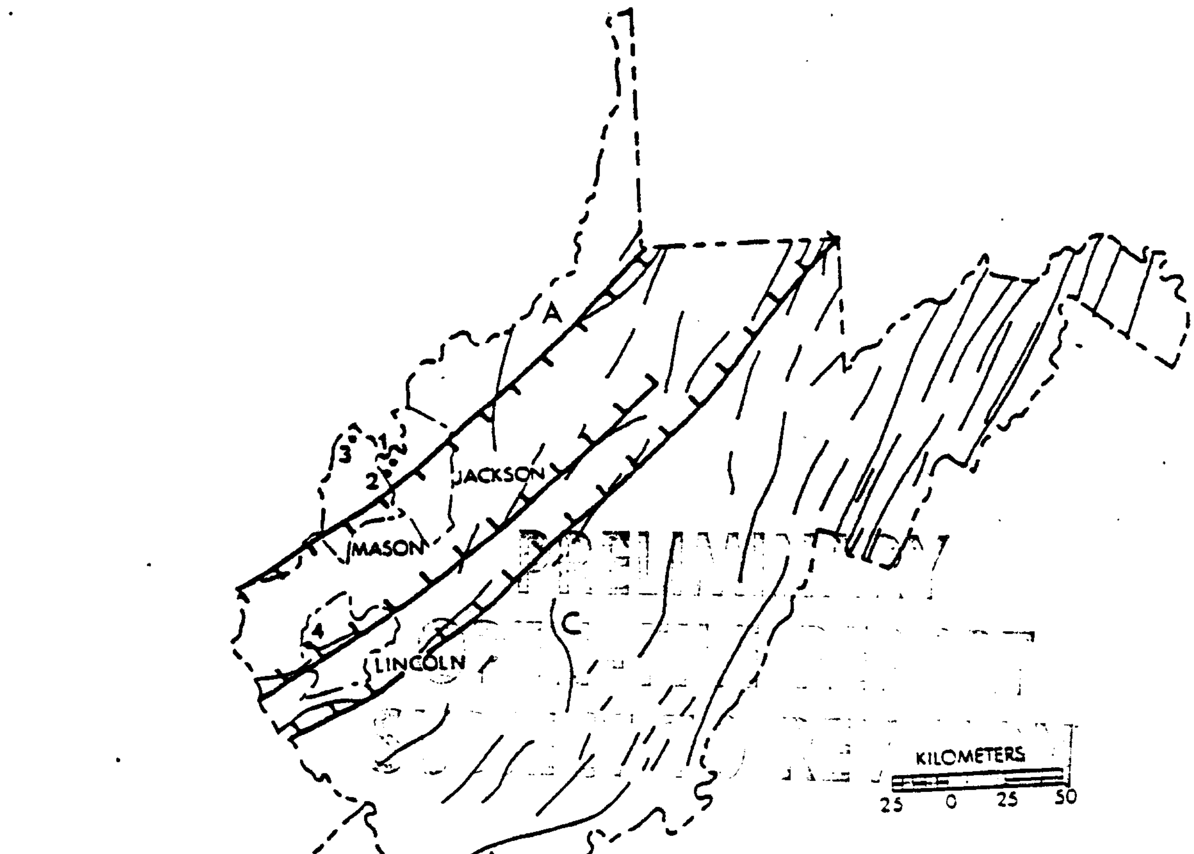

Figure 13 Structural setting of Devonian gas-shale wells used in this study: A) Rome Trough, B) Pine Mountain Thrust, C) anticline axes. County permit numbers of wells: 1) Jackson 1371, 2) Jackson 1369, 3) Mason 146, 4) Lincoln 1637, 5) Wise 253.

Macroscopic and Microscopic Fractures

Macroscopic natural fractures in core samples were distinguished from induced samples using the criteria of Kulander et al.(1977). In addition to the 94 fracture samples collected, 450 thin sections and X-radiographs of the shale matrix in productive and nonproductive intervals were examined. Macroscopic fractures were initially divided into three groups on the basis of dip; high-angle fractures (dip 90-80^{o}), inclined fractures (dip 79-45^{o}), and low-angle fractures (dip 44-0^{o}) (Wallach and Prucha, 1979). Although this classification does yield three well defined classes, the presence of gas shows is not strictly delineated by these classes. In order to better characterize gas producing fractures, macroscopic fractures were subsequently placed into two classes, those associated with gas shows and those not associated with gas shows.

Current models of gas production from Devonian gas-shale wells invoke a dual porosity reservoir in which the macroscopic fracture porosity system is recharged by gas migrating out of the shale matrix (Smith, 1979). Microscopic fractures may contain gas and serve as conduits for gas migration. Examination of natural fracture surfaces and the shale matrix adjacent to natural fractures by scanning electron microscopy, transmitted light microscopy, and X-radiography failed to detect a significant microscopic fracture system. The resolution of our electron microscope is 125 angstroms. Microstructures searched for include, intergranular and intragranular fractures, microdisplacement along grain boundaries, and preferred grain orientation suggestive of microdeformation.

At the fracture front of some macroscopic fractures, microscopic fractures, 1-2 mm in length, were observed in the shale matrix. These microscopic fractures represent the incipient growth of the advancing macroscopic fracture through the rock matrix and are only preserved if the macroscopic fracture stops advancing at that point. Larese and Heald (1977) described microscopic fractures produced by compaction of the shale matrix around large pyrite nodules in samples from Jackson 1369. This type of microscopic fracture is not common and is localized around the pyrite nodule.

Matrix porosity and permeability determinations on core samples do not support the existence of a microscopic fracture system. The mean matrix porosity (2.2%) of the productive lower portion of the Huron Member is higher in Lincoln 1637 (85 MCFD - natural open flow) than in Jackson 1369 (1007 MCFD - natural open flow). Permeability tests by Core Laboratories on selected core samples from Jackson 1369 containing no macroscopic fractures were not significantly different from these of less productive shale-gas wells. The mean matrix permeability of the black shale is .005 millidarcies. If a microscopic fracture system capable of storing or transmitting gas is present, it should be reflected in higher matrix porosity and matrix permeability for the more productive wells. These tests are in agreement with the visual observations that no significant microscopic fracture enhancement of porosity and permeability exists. We conclude that only macroscopic fractures are of importance in gas production from the Devonian shale sequence.

Macroscopic Fractures Associated With Gas Shows

Fractures associated with gas shows in the shale sequence must be partially open to enhance permeability and porosity. Mechanisms for keeping fractures open at depth include high pore fluid pressure (Secor, 1965) and physical propping. Since the Devonian shale section in the study wells is not overpressured at the present time, many fractures must be propped open.

Mineralization is a common type of propping. Some mineralized fractures have corresponding gas shows. A gas show (105 MCFD) in the upper-middle portion of the Huron Member in Lincoln 1637 is associated with a zone of high-angle fractures, 1-2 mm wide, mineralized by dolomite and barite (Fig. 14). Porosities of the fracture fillings, calculated from bulk density and grain

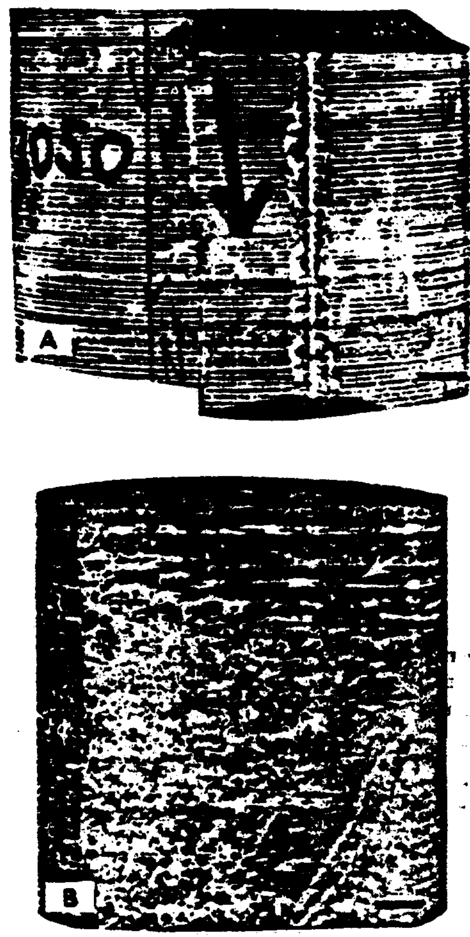

Figure 14. Mineralized fractures associated with gas shows. A). High-angle fracture (white arrow) from Lincoln 1637 partially cemented by dolomite and barite. Fracture has 20% intercrystalline porosity. B). Fracture surface in black shale from Mason 146 covered with scattered, euhedral dolomite crystals. The crystals line up (arrow) along interbedded silt lenses. Scale bar is 1 cm.

density measurements, ranged from 3-20%. Attempts to impregnate the fillings with resin to observe pore geometry failed with the low porosity fillings suggesting that their permeability is also low. The high porosity fracture fillings yielded pore casts. The degree of interconnection between the intercrystalline pores formed a very permeable conduit for gas flow into the well bore.

A good example of a partially mineralized fracture associated with a gas show (200 MCFD) was found in the lower portion of the Huron Member in Mason 146. A high-angle fracture, 1.5 mm wide, had scattered, euhedral dolomite rhombs on its surface (Fig. 14). Where interbedded silt lenses were present, the dolomite crystals lined up along them. In thin section, the silt lenses were seen to be tightly cemented by dolomite. The dolomite in the silt lenses probably acted as seed crystals for crystals precipitating from solutions in the fracture.

Siltstones and silt lenses in the cores examined are commonly cemented by dolomite, siderite, or calcite. Migrating pore water from the compacting shale likely transported the ions necessary for cement formation (Curtis, 1978). Fracture mineralization in the study wells postdates cementation in the siltstones and silt lenses as determined from cross cutting relationships observed in thin section. The mineralized high-angle fractures show no evidence of compaction which might be expected if shale dewatering and compaction was a factor in their formation. Smectite dehydration may have provided a source of late diagenetic water. Water bearing Devonian, Silurian and Cambrian sandstones and limestones underlie the Devonian shale section, but their role as a source for the fracture filling fluids is unknown.

Offset along fracture surfaces is interpreted as a second mechanism for maintaining open fractures in Devonian shales. Fracture surfaces in rock are characterized by transient features of varying relief (Kulander et al., 1977) (Fig. 15). Fracture porosity can be produced by offsetting and subsequent

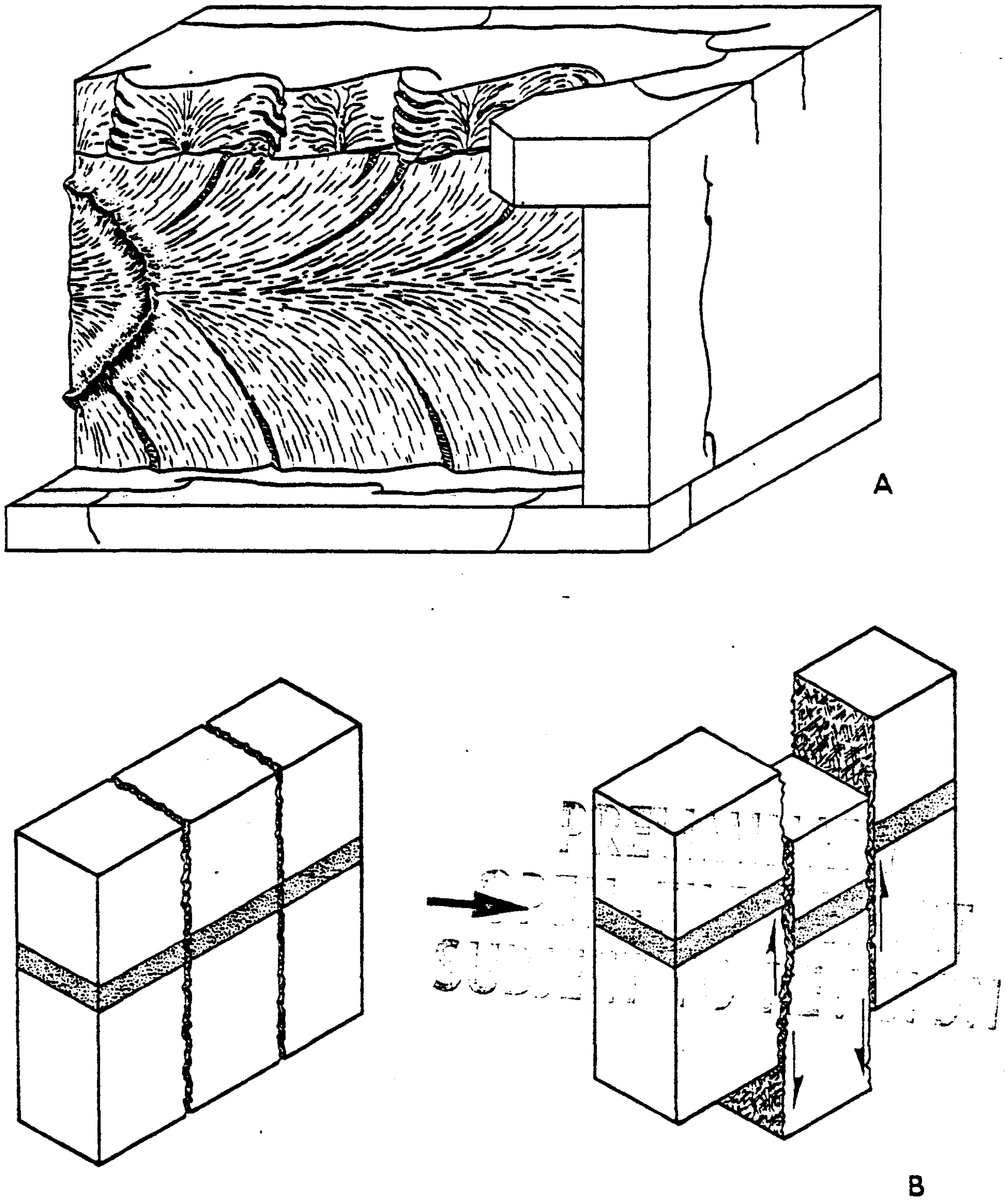

Figure 15. Illustration of offsetting creating permeability and porosity. A). Surface features of a fracture surface. (Kulander, 1977). The relief of fracture surface hackles observed in Devonian shales ranges from 14 mm to less than 1 mm. B). If offsetting movement occurs while the fracture is open, the fracture can be subsequently held open by propping along the irregular fracture surfaces. Amount of open space produced depends on the relief of the fracture surface and the extent of later mineralization.

propping along these uneven surfaces. Depending on how the fracture width, the relief of the surface hackles, and the angle of movement, portions of the opposing fracture surfaces may grind against each other forming small slickensided areas on the fracture surface. The fracture could also open, undergo a relative shift of opposing surfaces and partially close without the fracture surfaces grinding against each other. The relief of fracture surface hackles observed in core samples ranged from 14 mm to less than 1 mm.

Offsets marked by slickenside portions of fracture surface hackles are present in Lincoln 1637 (Fig. 16). After the fractures were opened and offset, they were cemented by dolomite crystals which show no evidence of fracturing or displacement, indicating that they precipitated after the offsetting movements.

The best example of offset fractures forming permeable conduits can be seen in Jackson 1369. In the lower portion of the Huron Member (1107 MCFD-natural open flow) numerous natural fractures were observed (Fig. 17). Some were tightly cemented and probably did not contribute to the large gas show. Many high-angle and inclined fractures showed evidence of offsetting and were only partially mineralized. The maximum observed relief of fracture surface hackles that showed evidence of offsetting was 14 mm (Fig. 17). Resultant vugs with a maximum width of 28 mm could be formed when opposing hackles abutted against each other. These large vugs were not completely infilled by later minerlization. Offset fractures were observed in core samples over a 6 mm interval that correlated with gas influx indicated by a temperature log. The high frequency of offset fractures in this well is likely produced by small movements of a normal basement fault located 1000 m south of Jackson 1369 (Martin and Nuchols, 1976; Sundheimer, 1978).

A high-angle fracture in the lower portion of the Huron Member in Lincoln 1637 showed no mineralization, but was open as evidenced by a gas show

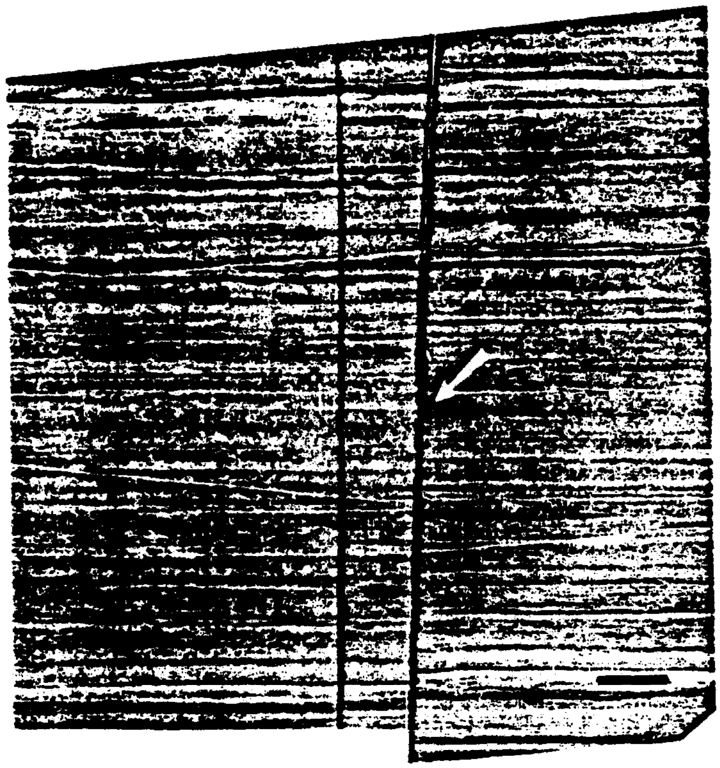

Figure 16. X-radiograph of high-angle fracture from Lincoln 1637 showing slight offsetting of opposing fracture surfaces (arrow) prior to mineralization. Porosity of dolomite filling is 3%. Large, white voids in upper part of fracture are due to sample preparation. Scale bar is 1 cm.

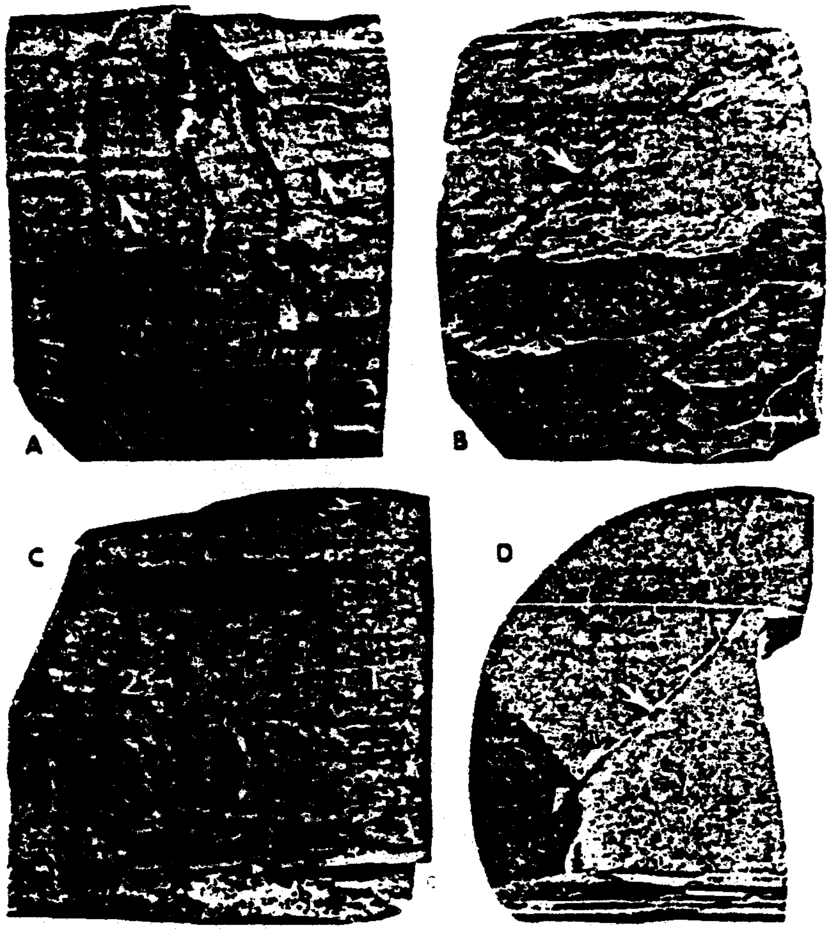

Figure 17. Natural fractures from the productive interval in Jackson 1369. A). High-angle fracture in black shale showing prominent hackles. Portions of the hackles are marked by vertical slickensides (arrows) indicating vertical offsetting between opposing fracture surfaces. Maximum relief of hackles is 14 mm. B). Inclined fracture (dip, 60°) with slickensided hackles (dark patches running diagonally (arrow) across the sample. Relief of hackles is 2-3 mm. Void space was partially infilled by dolomite (light patches) after the slickensides formed. C). Intersection (60°) of two partially mineralized fractures. Fracture surface (1) did not propagate past fracture surface (2) as observed on the complete core sample. D). Partially mineralized cross-fracture (arrow) between two tightly-cemented vertical fractures. This short fracture only causes a local increase in rock permeability, but larger fractures of the same orientation may exist. Scale bar is 1 cm.

(87 MCFD) (Fig. 18). By measuring core diameters parallel and perpendicular to the fracture, it is estimated that the fracture was open .5-1 mm. No evidence of offsetting and propping along fracture surfaces was observed on the core sample, but it is likely that the fracture was propped open somewhere along its extent. Lincoln 1637 is not located on a structure that would form open, crestal tension fractures. This fracture may instead be related to erosional unloading (Currie, 1977). With 30 m above and below this open fracture, tightly closed, unmineralized high-angle fractures were found. It is difficult to predict the occurrence of open fractures when fractures of the same dip, orientation, and rock type in a given well show no consistent pattern.

Macroscopic Fractures Not Associated With Gas Shows

In the Devonian shale section of the Appalachian Basin, the average gray shale contains .1 cfg/cfs, and the average black shale contains .6 cfg/cfs measured under ambient conditions (Smith, 1978). Natural fractures not associated with gas shows in gas bearing rocks must be closed or have little permeability due to tight cementation. One core sample from Wise 253 contained three high-angle fractures, 1.5 mm wide, which were tightly cemented by dolomite (Fig. 19). Many of the individual crystals in the filling extend across the width of the fracture and effectively seal it (Fig. 19). Fractures tightly cemented by a mosaic of anhedral dolomite crystals were found in Lincoln 1637 and Mason 146 (Fig. 19). The degree of cementation may be related to fracture frequency and fracture length. Given a limited volume of mineralizing fluids, short or widely spaced fractures might tend to be cemented more tightly than large or closely spaced fractures. Jackson 1369 had the highest number of partially mineralized fractures and the highest fracture frequency in a productive interval among the wells studied.

Examples of closed, unmineralized high-angle fractures in gray and black

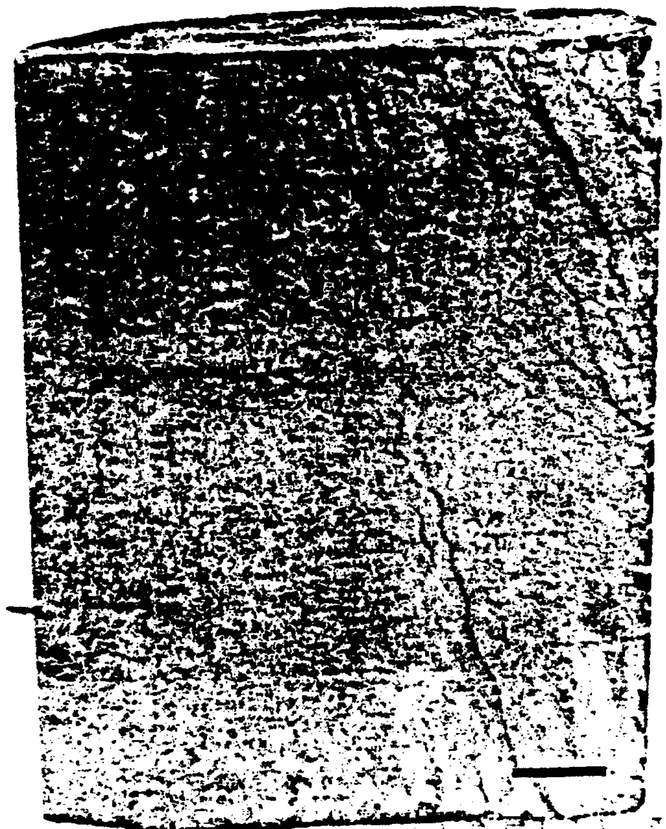

Figure 18. Unmineralized high-angle fracture associated with a significant gas show in Lincoln 1637. Scale bar is 1 cm.

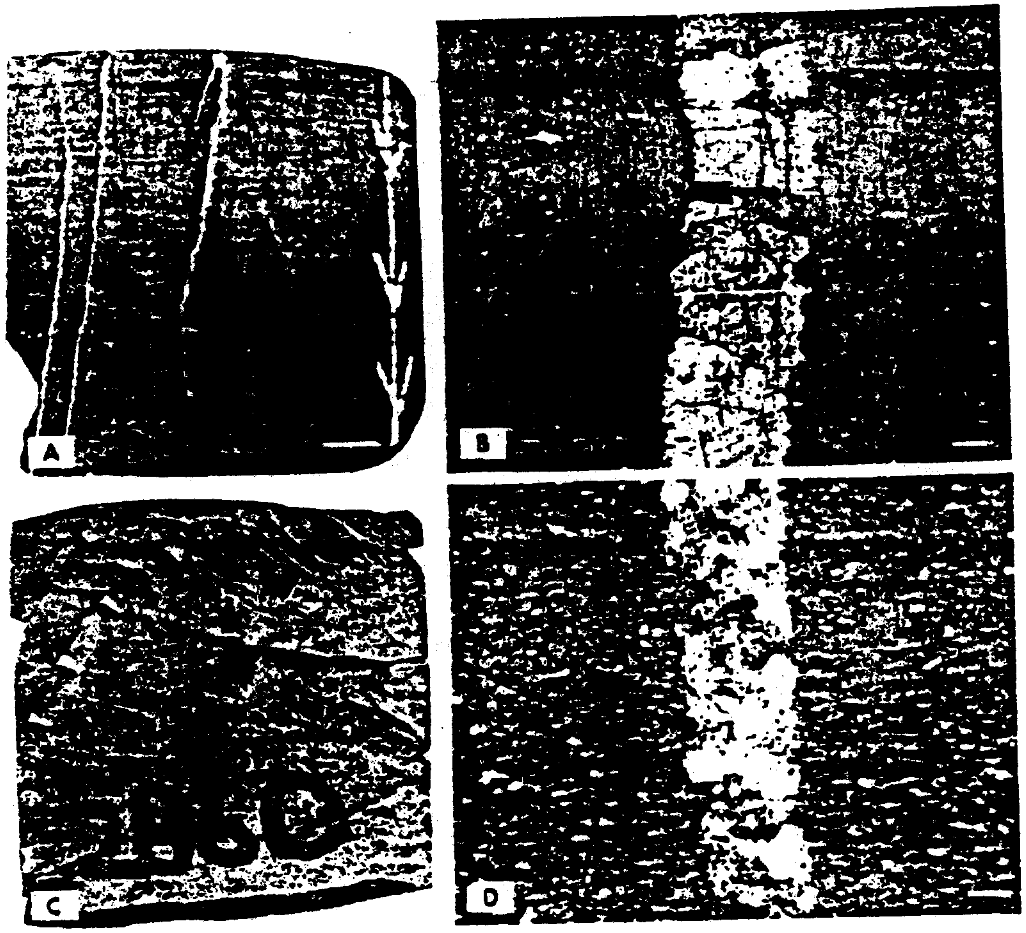

Figure 19. High angle fractures not associated with gas shows. A). Mineralized high-angle fractures in black shale from Wise 253. The fractures may be quite short as two of them terminate in the core sample. B). Photomicrograph of fractures from A. Many of the individual dolomite crystals (arrow) extend completely across the fracture. C). Unmineralized high-angle fracture from Mason 146 showing termination of natural fracture front (arc marked by arrows). The fracture was tightly closed at depth. D). Photomicrograph of high-angle fracture from Mason 146 tightly cemented by a mosaic of anhedral dolomite crystals. Scale bar is 1 cm in core samples amd .1mm in photomicrographs.

shales were present in Lincoln 1637 and Mason 146 (Fig. 19). None of the fractures showed any evidence of offsetting or propping. Fracture length may be a controlling factor. For offsetting along fracture surfaces to occur, it seems necessary for a fracture to interconnect laterally with other fractures forming fracture bounded blocks which might shift position slightly when the fractures are open.

No low-angle fractures were associated with gas shows. Low-angle fractures were found in every core, but were most common in the Wise 253 core from the Pine Mountain thrust plate. All low-angle fractures were slickensided and many were cemented by fibrous dolomite and ferroan dolomite (Fig. 20). Durney and Ramsey (1973) interpreted elongate fibrous or needlelike crystals as representing syntectonic crystal growth in a progressively opening fracture. Little permeability or porosity can exist when individual crystals consistently span the fracture.

Electron microscope examination of slickensided surfaces showed complete obliteration of grain to grain boundaries as a result of crushing and grinding of the grains on opposing rock surfaces (Fig. 20). The sheared surface likely forms a permeability barrier to gas migration from the shale matrix. Although most low-angle fractures are tightly closed, a small number have small voids between opposing fracture surfaces in which sulfate and carbonate crystals precipitated (Fig. 20). These pores are not interconnected and do not increase the permeability of the fracture. The amount of movement necessary to form a slickensided surface (obliteration of grain to grain boundaries) could not be measured in most samples. An X-radiograph of a closely spaced set of inclined, slickensided fractures from Lincoln 1637 showed that displacements as small as 3 mm could produce a slickensided surface (Fig. 20).

Low-angle fractures possess a variety of surface markings. Some have well developed fine striae or mirror like surfaces while hackles similar to those

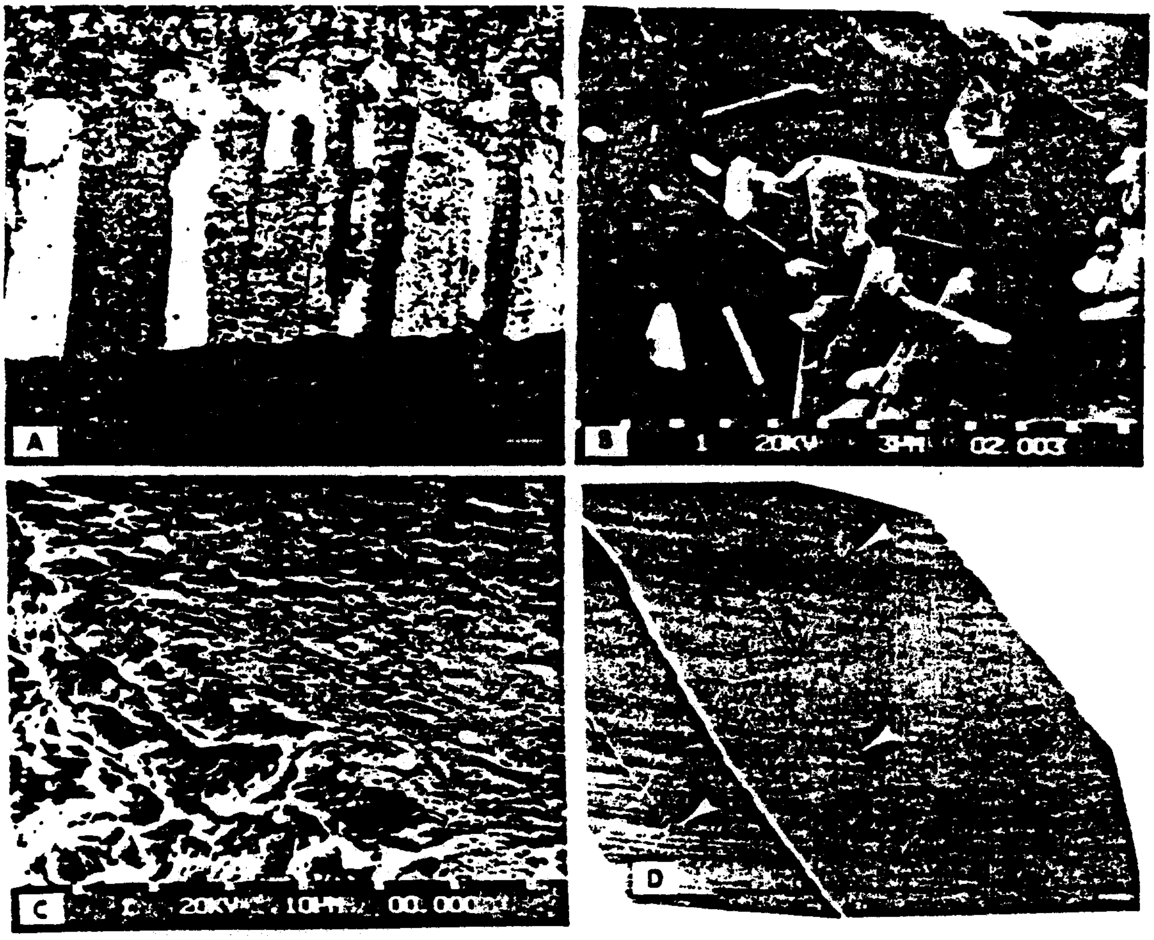

Figure 20. Characteristics of low-angle fractures. A). Photomicrograph of fibrous dolomite crystals in a tightly-cemented low angle fracture from Wise 253. Scale bar is .1 mm. B). SEM micrograph of gypsum crystals in a small vug on a slickensided low angle fracture from Wise 253. C). SEM micrograph of a natural slickensided surface (right) adjacent to an artificial fracture in the shale matrix. Grain to grain boundaries are completely destroyed, forming an impermeable surface. D.) X-radiograph of a set of inclined slickensided fractures showing slight offsets (arrows). Large white voids reflect parting along the fractures during sample preparation. Fractures were tightly closed in the core sample. Scale bar is .5 cm.

found on high-angle fractures are present on others (Fig. 21). The fractures surfaces are slickensided, but insufficient movement occurred to completely destroy the surface hackles. En-echilon tension fractures filled with fibrous calcite or dolomite crystals were observed in close proximity to some low angle fractures (Fig. 21). A fault breccia from Lincoln 1637 contained pieces of shale rotated at least 90^{o}, but pyrite cementation prevented any increase in permeability (Fig. 21).

Natural Fracture Permeability and Porosity

The contribution of open fractures to the permeability of a Devonian shale gas reservoir is high given the low permeability of the rock matrix, but their contribution to porosity is not accurately known. Schettler (1978) maintains that gas contained in natural fractures in the shale reservoir is depleted in a short time (hours to weeks) and that most gas eventually produced migrates from the shale matrix into permeable fractures which connect with the well-bore. Fracture surface area is one factor controlling well productivity because it determines the volume of the gas bearing rock matrix being drained. In a ten year period, 40 cc of gas migrates from the shale matrix through each square centimeter of the fracture surface (Schettler, 1978). In this regard, high angle and inclined fractures would be more efficient in draining the rock matrix than slickensided, low angle fractures. Wise 253 and Jackson 1371 had no natural open flow, but both wells produced at modest rates after stimulation. The induced fractures probably communicated with natural fractures that were open.

The fractures examined in the naturally productive intervals of the study wells do not appear to contribute greatly to porosity. As discussed previously, mineralized fractures, 1-2 mm wide, with 20% intercrystalline porosity correlated with significant gas shows. Although the amount of fracture porosity in the Devonian shale sequence can never be directly measured,

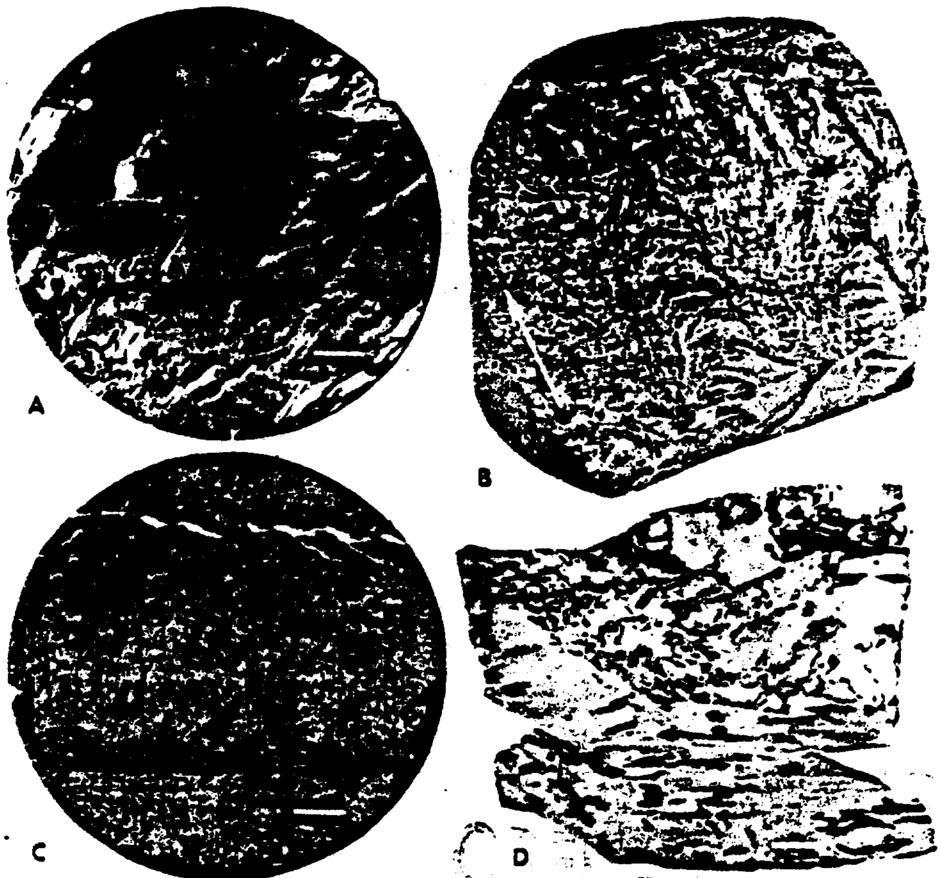

Figure 21. Other natural fractures not associated with gas shows. A). Unmineralized, slickensided fracture surface from from Wise 253. Opposing fracture surfaces were tightly closed in the core sample. B). Slickensided fracture surface (dip 40°) with partially preserved hackles. Hackle orientation indicates that the fracture propagated upsection (arrow). From Lincoln 1637. C). En-echilon tension fractures from Wise 253 tightly cemented by fibrous dolomite crystals. D). X-radiograph of fault breccia from Lincoln 1637 cemented by pyrite (arrow). Scale bars are 1 cm.

limits on the value can be approached. For a cube of shale cut by two sets of vertical fractures with each fracture open 1 mm, the amount of fracture porosity can be calculated. If a fracture frequency of 1.2 m is assumed, fracture porosity is approximately 0.16%. A fracture frequency of .6 m yields a fracture porosity of 0.32%. This model (Fig. 22) assumes a much higher frequency of open fractures than is seen in shale cores and outcrops. Drummond (1964), in summarizing estimates of fracture porosities in fractured reservoirs, states that: "bulk fractured porosities in fractured reservoirs range down from three percent." Murry (1968) reported a fracture porosity of less than 1% for the Spanish pool, North Dakota and concluded that the major role of fractures in that pool is enhancement of permeability. A similar situation seems to exist for the Devonian gas shales of West Virginia and Virginia.

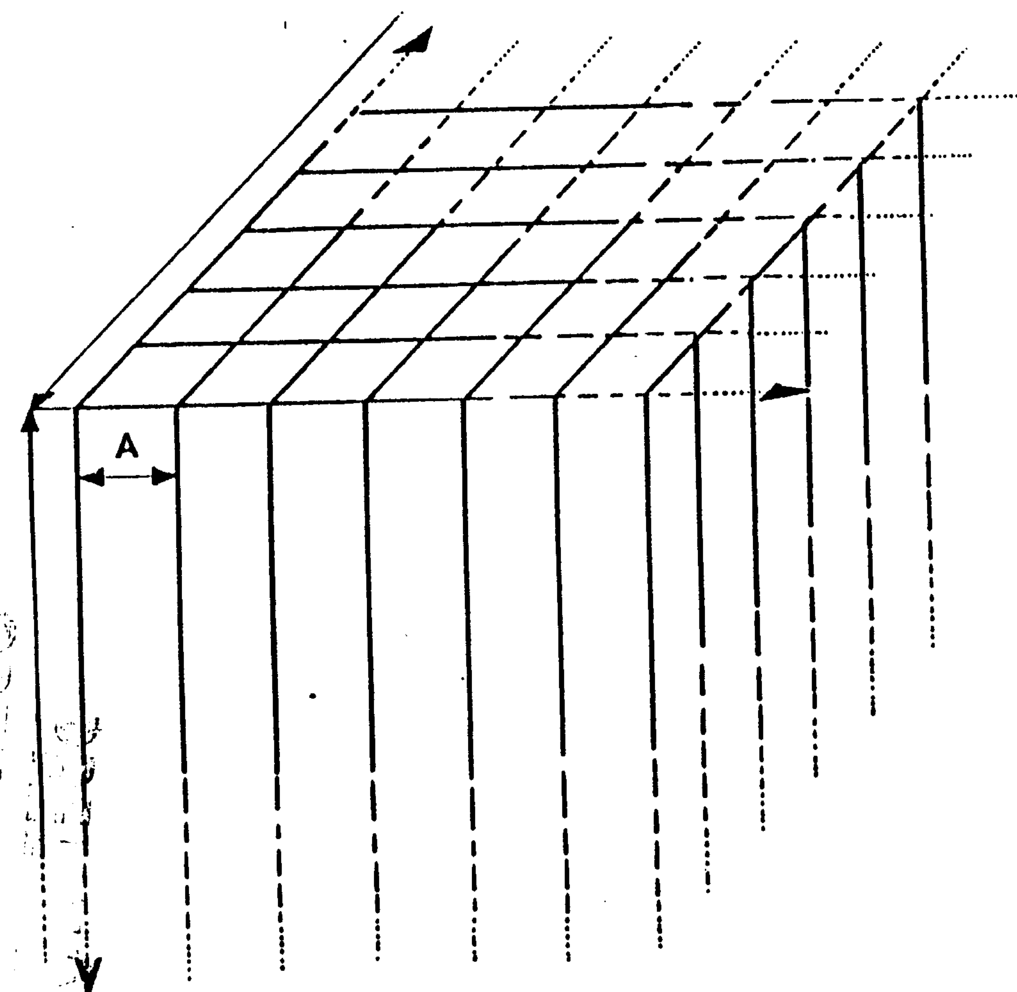

Figure 22. Model of possible limits to fracture porosity in Devonian shale. A block of shale is assumed to be cut by two sets of vertical fractures intersecting at 90° with each fracture open 1 mm. If fracture spacing (A) is 1.2 m, fracture porosity is 0.16%. If fracture spacing is .6m, fracture porosity is 0.32%.

CONCLUSIONS

1. Microscopic fractures are rare and do not significantly contribute to the porosity or permeability of the Devonian shale samples studied.

2. Gas shows in the Devonian shale sequence correlate with macroscopic natural fractures observed in cores. Many fractures have no corresponding gas shows due to tight cementation or closure at depth.

3. Low-angle fractures are not associated with gas shows. High-angle or inclined fractures which remain open due to partial mineralization and, or propping caused by offsetting along opposing fracture surfaces have corresponding gas shows.

4. Fracture porosity is apparently of only minor consequence in the Devonian shale sequence. The major role of fractures is enhancement of permeability.

5. A shale classification based on fabric elements is useful for investigating reservoir properties and for interpreting depositional environments. Four lithic types have been identified: 1) thinly-laminated shale, 2) lenticularly-laminated shale, 3) sharply-banded shale, 4) nonbanded shale. The order here, from 1-4, generally follows decreasing organic content, decreasing pyrite content and decreasing lateral fabric continuity.

6. Matrix porosity varies little between the lithic types and does not appear to be an important factor in well productivity.

7. Organic-rich thinly-laminated and lenticularly-laminated shale appear to be the most favorable types for gas production because the higher organic content of these shales acts as sites for significant sorption of gas, which is slowly released from the rock matrix.

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